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POLYMER COMPOSITES FOR EXTERNAL REINFORCEMENT OF BUILDING STRUCTURES

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Abstract: Key aspects of developing effective systems for the external reinforcement of building structures, made of composite polymer materials containing carbon fibers and no-bake polymer binders, ensuring shape formation in the temperature range of 15 - 40 °C no more than 24 hours, characterized by operability in the temperature range from minus 45 ° C to plus 60 ° C. PCM-based SVA has a number of advantages compared to clips and metal profiles traditionally used for repairing building structures: the load-bearing capacity of the rods increases, the cost of the strengthening of load-bearing structures is reduced, and the seismic resistance of engineering structures is increased. In relation to composite SVA building structures, the following types of construction chemicals are used: primer, putty, adhesive, protective coating. The production of unidirectional tapes was carried out on a Dornier double rapier loom, modernized for processing carbon fibers. The results of experimental studies of the developed polymer binders and carbon reinforcing fillers are presented. It is shown that the developed materials can be successfully used to strengthen and repair engineering structures. The technological features of strengthening and repairing building structures with composite external reinforcement systems using the contact molding method and ready-made lamellas are described. Installation of composite clamps on vertical surfaces is carried out by fixing the canvas in the extreme position, followed by laying, smoothing and rolling along its length. Rolling is done from the middle to the edges. Before gluing the blanks, the lamellas are laid out on a work table (workbench) and thoroughly wiped with a rag moistened with acetone. Results of the large-scale implementation of these new materials and technologies in the construction industry are presented.

Keywords: thermosetting matrix, reinforcing carbon filler, building structure, composite external reinforcement system, reinforcement, repair

ПОЛИМЕРНЫЕ КОМПОЗИТЫ ДЛЯ ВНЕШНЕГО АРМИРОВАНИЯ СТРОИТЕЛЬНЫХ КОНСТРУКЦИЙ

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Аннотация: Рассмотрены ключевые аспекты создания эффективных систем внешнего армирования строительных конструкций полимерными композитными материалами на основе углеродных волокон и полимерных связующих холодного отверждения, обеспечивающих формообразование в интервале температур (15 – 40) °С не более 24 часов, характеризующихся работоспособностью в интервале температур от минус 45 °С до плюс 60 °С. СВА на основе ПКМ обладает рядом преимуществ по сравнению с традиционно используемыми для ремонта строительных конструкций обоймами и металлическими профилями: несущая

способность стержней увеличивается, затраты на усиление несущих конструкций снижаются, повышается сейсмостойкость инженерных сооружений. Применительно к композитным СВА строительных конструкций применяются следующие типы строительной химии: праймер, шпатлевка, адгезив, защитное покрытие. Выработка однонаправленных лент осуществлялась на двурапирном ткацком станке фирмы Dornier, модернизированном для переработки углеродных волокон. Приведены результаты экспериментальных исследований разработанных полимерных связующих и углеродных армирующих наполнителей. Показано, что разработанные материалы могут успешно применяться для усиления и ремонта инженерных сооружений. Описаны технологические особенности усиления и ремонта строительных конструкций композитными системами внешнего армирования с использованием метода контактного формования и готовых ламелей. Установка композитных хомутов на вертикальные поверхности осуществляется фиксацией холста в крайнем положении с последующей укладкой, разглаживанием и прокаткой по длине. Прокатка производится от середины к краям. Перед наклейкой заготовки ламели раскладываются на рабочем столе (верстаке) и тщательно протираются смоченной ацетоном ветошью. Представлены результаты широкого внедрения созданных материалов и технологий в строительной отрасли.

Ключевые слова: термореактивная матрица, углеродный армирующий наполнитель, строительная конструкция, композитная система внешнего армирования, усиление, ремонт

1. INTRODUCTION

Development of advanced polymer composite materials (PCM) is impossible without advanced techniques in the field of construction materials and technologies [1-3]. Thus, in the process of curing, novel binders should not only form a high-strength polymer matrix, ensuring maximum strength of reinforcing fibers in materials, they should have high-tech characteristics, comply with the principles of "green chemistry", and ensure their recycling using inexpensive technologies.

However the curing process typical for traditional technologies applied to manufacture PCM products, containing thermosetting matrices, are characterized by high energy consumption, namely, those PCM products that contain hot-setting polymer binders. This process is time consuming (6 - 9 hours): a temperature rise is followed by a long-term exposure of the molded element to high temperature. Special autoclave equipment is frequently used for this purpose.

Cold-curing polymer binders, applicable in the temperature range between 15 and 40 °C, do not require any expensive and energy-consuming autoclave equipment. Their application facilitates the development of simplified energy-efficient and resource-saving PCM production technologies for the construction industry. Such technologies can be applied at the site of construction or renovation of a construction facility by using the so-called composite external reinforcement systems (ERS) [4 - 6]. Therefore, the task is to make PCM containing various reinforcing fillers (carbon, glass, mixtures) and polymer binders for ERS of building structures, using the contact molding method that ensures the forming process in the temperature range between 15 and 40 °C within 24 hours. These building structures can be operated in the temperature range from minus 45 °C to plus 60 °C.

In the Russian Federation, the annual building reinforcement market capacity is about 5 billion rubles; it depends on the rate of (1) repair of worn-out infrastructure and (2) construction. The market capacity of external PCM reinforcement is about 850 mln. rubles, and its rate of growth is 15 – 20% per year. In the future, replacement of existing repair materials with PCM can boost the demand for PCM to 200 million rubles per year.

It is necessary to emphasize the expanding application of PCM containing carbon and hybrid fabrics, laminates and meshes by the construction industry [7 - 9]. In Switzerland, these materials are already used in more than 80% of cases of reinforcement of reinforced concrete, masonry and metal building structures. According to the experts, the global market of such PCMs is expected to double in the coming 5 - 7 years.

Composite ERS, entering the construction industry market, should contribute to the solution of the following problems [10 - 13]:

- ensuring the repair of load-bearing elements of reinforced concrete, masonry, and metal structures featuring substantial wear and tear;
- ensuring the reconstruction of load-bearing elements of structures in a short period of time, if the main items of equipment are replaced;
- increasing the "survivability" of buildings and structures subjected to natural and man-made factors, including terrorist attacks.

PCMs entered the construction market quite recently, although they are known to be in use abroad since the late 70s of the 20th century. In the Russian Federation they are used since the late 90s, and are widely used in foreign and domestic construction industries.

ERSs containing PCMs have a number of advantages compared to cases and metal shapes traditionally used to repair building structures [14, 15]:
- the load-bearing capacity of structures increases by 70% (including complex geometric shapes and cases of confined spaces) without any substantial increase in their weight, while there is an additional opportunity to correct inaccuracies that may arise at the design stage;
- the cost of reinforcement of load-bearing structures reduces by 20 - 60% due to the fact that there is no need to use heavy-duty equipment and to suspend the operation of a structure, which is extremely important, for example, for railroad bridges;
- the seismic resistance of engineering structures operated under such conditions increases by 2 - 3 grades.

2. EXPERIMENTAL STUDIES AND THEIR DISCUSSION

2.1. Construction chemicals for composite systems of external reinforcement of building structures

The following types of construction chemicals are used to make composite ERS building structures:

1. The primer used to ensure adhesion. The average primer consumption is 100 - 300 g/m^2.
2. The putty used to correct minor defects. Its composition differs slightly depending on the manufacturer; its consumption rate depends on the extent of structural damage.
3. The adhesive substance (the glue) used to bond tapes (if their length is up to 250 m; width up to 15 cm), canvases (if their width is 600 mm or up to 1500 mm, which is less frequent) (Figure 1a), and lamellas (pre-impregnated and cured tapes with aligned edges (length up to 100 m, thickness 1,2 – 1,4 mm) (Figure 1b) to the surface of the structure. The adhesive substance, applied to different types of materials, differs mainly in viscosity.

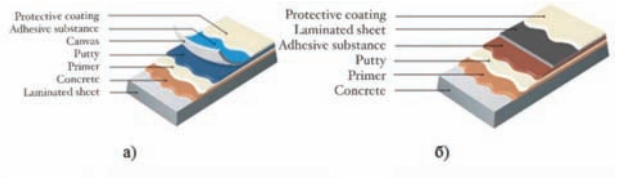


Figure 1. Lay-up sequence of ERS components for: a) tapes and canvases; b) lamellas

There are "dry" and "wet" methods of applying adhesive substance to canvas. The "dry" method involves applying the adhesive substance to the structure, then attaching the canvas and bonding it to another layer of adhesive over it. The "wet" method involves applying the adhesive substance to the tape/canvas, whose side that has glue on it is attached to the concrete of the structure and then bonded to another layer of the adhesive substance. The adhesive substance used for the "wet" method is more viscous. The main difference in the choice of application methods is the simplicity of application of the binder needed to bond the ERS reinforcement components. The adhesive substance is characterized by thixotropy and is generally the same if used to bond glass and aramid fibers. The consumption of the adhesive substance varies from 0,7 to 4 kg/m^2, depending on the brand and type of tape/canvas.

As part of the experimental research, compositions of primers, putties and adhesive substances were developed for composite ERS building structures and their properties were investigated. Table 1 shows physical and mechanical properties of the novel primer Fibarm resin 530+, putty FibArm Repair EP 301, and adhesive Fibarm resin 530+.

Table 1. Physical and mechanical properties of Fibarm resin 530+ primer, FibArm Repair EP 301 putty, and Fibarm resin 530+ adhesive substance

	Measurement unit	Value		
		primer	putty	adhesive
Modulus of elasticity in tension	GPa	≥ 0,5	≥ 3	≥ 3
Modulus of elasticity in bending	GPa	≥ 0,5	≥ 3	≥ 3
Tensile strength	MPa	≥ 20	≥ 40	≥ 40
Bending strength	MPa	≥ 20	≥ 40	≥ 40
Ultimate relative strain in tension	%	1 – 3	1 – 3	1 – 3
Mortar life time (at + 20 °C)	min	30 – 45	30 – 45	30 – 45
Application temperature	°C	+5 – +30	+5 – +30	+5 – +30
Operating temperature	°C	-40 – +60	-40 – +60	-40 – +60
Density of ready-mixed mortar	kg/l	1,0 – 1,1	1,5 – 1,7	1,0 – 1,3
Adhesion to concrete (steel)	MPa	≥ 3	≥ 3	≥ 3
Strength development time (at + 20 °C)	days	7	7	7

The critical strength development time is 30 - 40 min for each of the primer, putty, and adhesive substance.

4. As a rule, protective coating is not a mandatory component of the system of structural reinforcement, rather, it is a supplementary one; its functional purpose is fire resistance, aesthetics or anti-vandal properties.

Based on the development results and experimental studies, cold-curing polymer binders FibAm Resin 230+, FibAm Resin 530+, FibAm Resin HT+, FibAm Resin Laminate+ were developed and introduced into ERSs of building structures [16 - 19].

2.2. Experimental studies of the unidirectional carbon filler designed for external reinforcement systems of building structures

In the course of the research undertaking, JSC "Prepreg – MCM" conducted activities aimed at developing domestic reinforcing carbon fillers. Let's analyze the development process and use the unidirectional carbon fabric as an example.

In foreign and domestic literature, materials with a width of up to 400 mm are usually called tapes; the material whose width exceeds 400 mm is called fabric. Thus, the carbon fiber filler, having unidirectional structure, will be called a unidirectional tape. Therefore, the technology was tested, the pilot batch was produced, and the stability of characteristics of prototypes of a carbon fiber filler featuring unidirectional structure was studied. The filler fastened with a thermoplastic mesh was also analyzed.

Unidirectional tapes were produced using a Dornier double rapier loom, modernized for the processing of carbon fibers. Up to five canvases can be produced simultaneously depending on the width of carbon tapes. Since the material being manufactured must have particular physical and mechanical properties, Umatex UMT49-12K-EP carbon filament with a linear density of 760 tex was chosen as the raw material for the warp filament. Its basic physical and mechanical characteristics are provided in Table 2.

Table 2. Physico-mechanical characteristics of carbon filler Umatex UMT49-12K-EP

Raw material	Characteristics	Values
Filament Umatex UMT49-12K-EP 760 tex	Linear density, tex	760
	Fiber density, g/cm^3	1,78
	Mass fraction of finishing agent	0,8 ± 1,5
	Modulus of elasticity, GPa	260
	Breaking tensile stress of filament (elementary), MPa	4900

Glass filament with polymer coating was used as filling yarn; its technical characteristics are provided in Table 3.

Table 3. Technical characteristics of glass filament with thermoplastic coating

Raw material	Characteristic	Value
Glass filament with thermoplastic coating 70 tex	Linear density, tex	87,5
	Mass fraction of polymer in filament, %	50
	Breaking tensile stress of filament, N/decitex	3,5

In the process of manufacturing specimens of unidirectional carbon tapes from UMT49-12K-EP carbon filaments, a double rapier loom with a weaving width of 1700 mm, equipped with a bobbin holder for 1200 bobbins, was used. To produce a 300 mm-wide tape with a warp filament density of 1,5 filaments/cm, 45 carbon fiber bobbins are required. The existing bobbin holder was modified to produce the required unidirectional carbon fiber tape. Filament guides and collectors with ceramic eyes were removed from the bobbin holder, and new ones were installed. Thus, the filament, leaving the bobbin and reaching the feed shaft of the DORNIER weaving machine, had no contact with neighboring filaments and was clearly oriented in space (without torsion). The bobbin holder threading scheme and photograph are shown in Figure 2.

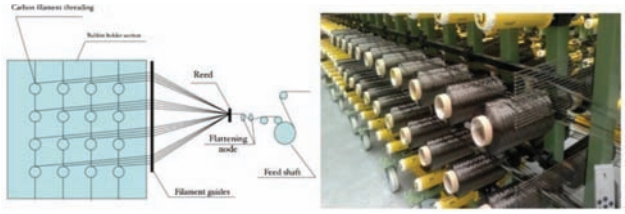


Figure 2. Scheme and photograph of bobbin holder threading

One of the requirements for the properties of a unidirectional tape was the minimum distance between warp filaments. However, this could not be achieved when standard heddles were used (Figure 3a). The main weakness of this type of heddle is the oval shape of the eye. At the moment of full opening of the gap, maximum tension arises in warp filaments, since they come into contact with part of the filament-conducting eye of the heddle. As a result, the carbon yarn changes its shape, and gaps emerge on the tape surface. To eliminate this defect, special heddles were selected that made it possible to maintain the flat structure of the carbon bundle at the moment of peak stresses during gap formation. Special heddles were made with an accuracy of 0,01 mm; they are shown in Figure 3b. The heddle, developed by the authors, has two parallel plates connected by a metal cylinder. Top and bottom cylinders serve to strengthen the structure, since the heddle walls are made of metal 0,3 mm thick. A pair of central cylinders act as a filament guide element. The distance between the heddle walls corresponds to the width of the carbon warp filament.

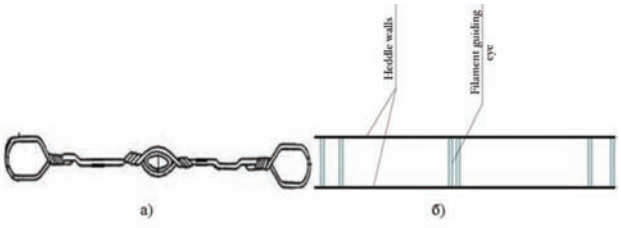


Figure 3. Types of heddles: a) twisted wire heddle; b) special heddle

Heddles are located on heddle frames, strictly parallel to the teeth of the reed. As part of the research, a special reed with a tooth wall thickness of 0,3 mm was designed and manufactured. When standard reeds were used, the fabric had large distances between warp filaments, since the standard version of a reed with a pre-set tooth density per centimeter has a wall thickness of 1,2 mm. The threading of filaments into the heddle of heddle frames and the rear reed is shown in Figure 4.

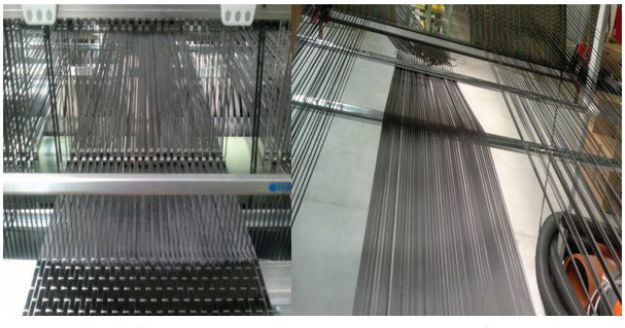


Figure 4. The threading of filaments into the heddle of a heddle frame (a) and the rear reed (b)

These unidirectional carbon tapes are similar to the UOL-300-R type tape. According to the specifications, the yarn filament density of the prototype is 1,2 ± 0,3 filaments/cm. Therefore, when this type of tape was produced, the yarn filament density varied from 1,2 to 0,9 filaments/cm. The yarn filament density of 0,9 reduces the surface density of the tape. The optimal operating parameters are as follows: the machine speed is 120 rpm of the main shaft of the machine; the infrared lamp temperature is 120 °C. The photograph of the carbon tapes, developed by the authors, is shown in Figure 5.

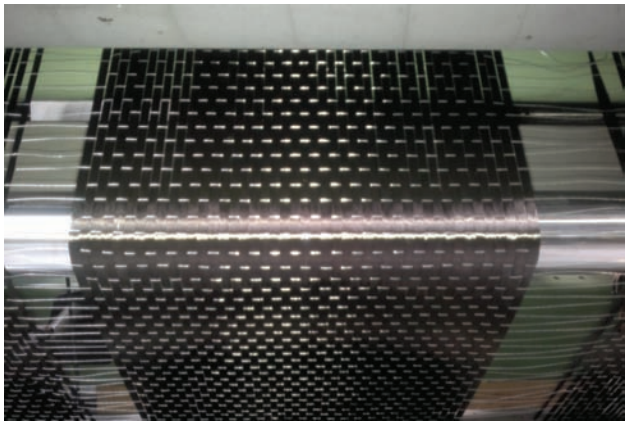


Figure 5. Unidirectional carbon tape St-1105

Based on the research results and experimental studies, reinforcing fillers titled Fibarm Tape 230, Fibarm Tape 530, containing carbon fibers, were developed and implemented for ERS of building structures.

2.3. Technological characteristics of reinforcement and repair of building structures using composite external reinforcement systems

The requirements, applied to the installation of composite ERS, depend on the type of material and raw materials used for its manufacture. Thus, lamellas are PCM, while canvases, tapes and fabrics are raw materials for PCM production. Composite lamellas should be bonded to smooth surfaces. Contact molding using fabrics, canvases and tapes, impregnated directly on the facility being repaired, is possible on variable-geometry (curvilinear) concrete surfaces.

The process of reinforcing the structure with Fibarm Tape canvases, developed by JSC "Prepreg - MCM" is shown in Figure 6. The installation of composite clamps on vertical surfaces is carried out by fixing the canvas in the extreme position, followed by laying, smoothing and rolling along the length. Rolling is done from the middle to the edges. Before gluing, lamellas are arranged on the workbench and thoroughly wiped with a rag moistened with acetone. The 1 – 2 mm layer of the adhesive substance is applied to the prepared concrete surface.

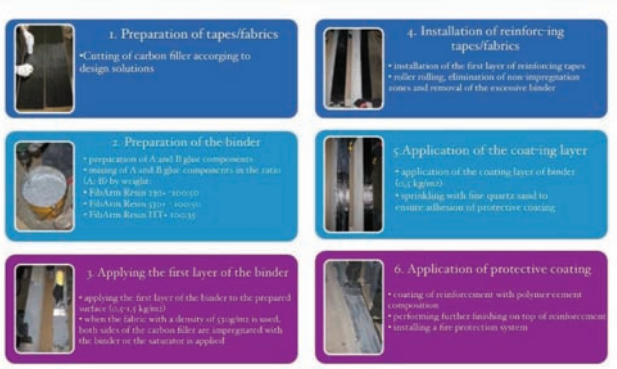


Figure 6. The process of surface reinforcement using Fibarm Tape canvases

This done, an Δ-profile is formed from the adhesive substance on the completely dry lamella surface using a specially manufactured dispensing device (conductor) or trowel; the thickness of the adhesive layer in the middle should be 2 mm, reaching 1 mm towards the edges. The process of surface reinforcement with Fibarm Laminate lamellas is shown in Figures 7 and 8.

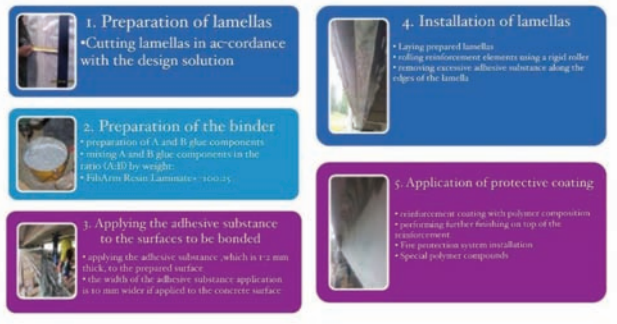


Figure 7. Process of surface reinforcement using Fibarm Laminate lamellas



Figure 8. Installation of Fibarm Laminate lamellas

After applying the adhesive substance, the lamella is laid over the base and rolled with a rigid roller to remove air from the adhesive layer. Excessive adhesive substance is removed with a spatula. In the case of gluing several layers of lamellas, they are preliminarily glued on the workbench, cured during the polymerization period of the adhesive substance, and then the laminated sheet is glued to the base.

3. USING NOVEL COMPOSITE MATERIALS AND EXTERNAL REINFORCEMENT TECHNOLOGIES TO REINFORCE AND REPAIR BUILDING STRUCTURES

These novel materials and technologies are widely used at more than 300 facilities in the Russian Federation and CIS countries [20-25].
During the operation of the building of the History Museum (Moscow), technological and design parameters of the building changed due to new access holes needed for utility pipelines. The strength values of some floor slabs was unacceptably low due to the lack of reinforcement. The deficit of strength was identified as a result of calculations and the survey data. A decision was made to strengthen sections of structures using carbon fiber Fibarm canvases and the cold-curing binder.
The appearance of the structures before the reinforcement is shown in Figure 9.



Figure 9. The appearance of structures of the History Museum building before the reinforcement

The appearance of the structures after the reinfrocement is shown in Figure 10.



Figure 10. The appearance of the reinforced structures of the History Museum building

The load-bearing capacity of the floor slabs was restored as a result of the repair activities aimed at the reinforcement of load-bearing structures with carbon-composite polymer materials.
Another interesting project that involved the use of composite ERS was the reinforcement of hollow-core slabs in the building of the Government House of the Russian Federation. The appearance before the reinforcement activities is shown in Figure 11a; the post-reinforcement appearance is shown in Figure 11 b.
The reinforcement was carried out in accordance with the customized engineering solution. Composite ERS installed on site ensure the design level of loading as well as the safe operation of the building.



а) б)

Figure 11. Structural elements of the building of the Government House of the Russian Federation: a) before reinforcement; b) after reinforcement with composite ERS

4. CONCLUSIONS

Given the results of integrated projects implemented in 2013 – 2023 and focused on the development of new generation PCM production technologies and design solutions for the construction industry, also implemented within the framework of Subprogram 14 “Development of production of composite materials (composites) and products” of the State Program of the Russian Federation titled “Development of the industry and increasing its competitiveness” and others programs, the authors obtained and implemented the following specific results:

- the production of woven (unidirectional and bidirectional) and non-woven materials for ERS with a tensile strength of, at least, 3 GPa and the elastic modulus of 200 GPa, the surface density of 230 - 530 g/m^2, width of 150 - 600 mm, suitable for reinforcing any types of structures (concrete, masonry, metal) was arranged;
- the production of carbon fiber lamellas using the pultrusion method with lamellas having a tensile strength of, at least, 2,9 GPa and the elastic modulus of, at least, 150 GPa was arranged;
- the pilot production of carbon anchor cable with a diameter of 10 - 20 mm and a tensile strength of, at least, 3,7 GPa, and the elastic modulus of, at least, 230 GPa was arranged to ensure the seismic reinforcement;
- the pilot production of two types of carbon meshes (dry and pre-impregnated with polymer compositions) for ERS with a tensile strength of, at least, 2,6 GPa, and the elastic modulus of 180 GPa was arranged;
- the pilot production of cold-curing epoxy binders for impregnation of carbon and hybrid ERS materials with adhesion to concrete, equaling, at least, 3,5 MPa, and glass transition temperature of, at least, 60 °C, was arranged;
- the pilot production of heat-resistant polymer cold-curing binders (glass transition temperature not less than 100 °C) was arranged;
- sets of engineering and design documentation, albums of standard solutions and software for the design and reinforcement of building structures, including those used in seismic zones, by composite ERS, were compiled;
- albums of standard solutions and software for ERS were compiled;
- novel engineering solutions were implemented at more than 300 facilities in Russia and abroad.

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