Composite materials in building structures using 3D technology

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Abstract. In recent years, composite materials have occupied a significant place among building materials. Among them can be distinguished glass and carbon fiber, which are largely distributed in construction. They are widely used in the reconstruction of concrete structures, for the production of structural products - as a substitute for some metal and stone structures, which is caused, first of all, by their significant mechanical properties and lightness. However, their fragility and relative high cost is an obstacle to the widespread use of this material. The introduction of 3D-technologies allows to reduce the cost of manufacturing building structures from composite materials, to increase their quality and manufacturability. 3D technologies also simplify the erection process and enable the implementation of complex architectural solutions.

1. Introduction

In recent years, the development of the chemical industry has led to the appearance of a large number of composite materials (composites) [1-2], including construction [3-4]. This relatively new class of polymers consumes 35% of the world's composite production in the USA, 22% in Europe, and 43% in Asia [5]. Their most prominent representatives are fiberglass (SP) [6], carbon fiber (up) [7-9], basalt plastics (BP) [10] and organoplastics (OP) [11-12]. In the latter case, fibers for the manufacture of the composite are obtained in the processing of biomaterials [13].

The matrix of composite compositions is most often thermosetting resins - low-molecular-weight epoxy (grades ED-4, ED-5, ED-40), polyester, phenol-formaldehyde and other synthetic resins and compositions based on them [14]. They have good adhesion to fiberglass, and epoxy resins cure even at sub-zero temperatures. Less commonly, for the matrix of composites, thermoplastics are used - polyamides, polyethylene, polystyrene, etc. [15].

As a reinforcing filler of composite materials, evenly distributed and randomly directed chopped glass, carbon, basalt, and other fibers are used [8-10].

Fiberglass materials have a sufficiently high strength, low thermal conductivity, high electrical insulation properties and the ability to transmit radio waves. In the first reinforced fiberglass, the number of fibers was small, the fiber was introduced mainly to neutralize gross defects of a brittle matrix [15]. In modern conditions, the fiber content in fiberglass can reach 80% by weight. Fiberglass is a fairly affordable material, and is widely used in construction, production of window frames, etc. [16]. Atmospheric resistance with the determination of the service life of fiberglass building structures was considered in [17].
Carbon fiber reinforced plastics have a high level of strength and elastic characteristics, high values of long-term and fatigue strength, low density, and the ability to maintain their mechanical properties at low temperatures (-60 °C) [18]. The latest developments in this class of composites-carbon fiber based on nanocomposite binders without the use of solvents [19] - produce materials with specified properties, such as electrical and thermal conductivity, as well as improved isotropy, increased moisture resistance and durability.

Basalt plastics have a low crack resistance (brittle), density of 1.8 g / cm³, thermal conductivity 0.023 W / m·K, tensile strength – on average 400 GPa. The climatic stability of basalt plastics is given in [20-21].

Organoplastics are composites in which organic synthetic fillers are used, less often natural and artificial fibers in the form of bundles, threads, fabrics, paper, etc. The material may contain up to 40–70% of the filler. Organoplastics have a low density, relatively high tensile strength; high impact resistance and dynamic loads, but at the same time, low compressive and bending strength. In addition, they are lighter than glass and carbon fiber. An important role in improving the mechanical characteristics of organoplastics is played by the degree of orientation of the filler macromolecules [15-16].

Fiber-reinforced plastics (FRP) in architecture and construction are used for the manufacture of long-span structures: shells, pneumatic coatings, awnings, etc. Using the properties of plastics in compression, it is possible to construct domes, mesh coatings and shells, arches and other spacer structures [22].

The development of 3D technology goes further and constructions made using a drone (unmanned aerial vehicle) are already being created: for example, an experimental pavilion built in 2016–2017 was made in Stuttgart (Germany) with the help of several aircraft printing devices. German experts are implementing projects of awnings, prefabricated domes, furniture and other small forms [23].

Table 1 [24] shows the comparative characteristics of some composite and metal materials.

| Substance            | Density, kg/m³ | Tensile strength, MPa | Young's modulus, GPa | Specific strength, e×10⁶, km | Specific module, E×10⁶, km |
|----------------------|----------------|------------------------|----------------------|-----------------------------|-----------------------------|
| Carbon fiber         | 1450–1600      | 780–1800               | 120–130              | 53–112                      | 9–25                        |
| Fiberglass           | 2120           | 1926                   | 69                   | 91                          | 3,2                         |
| Polyamide 6,6        | 1140           | 82,6                   | 28                   | 7,24                        | 0,24                        |
| Polyamide 6,6 + 40% fiberglass | 1460 | 217                      | 112                  | 8,87                        | 0,77                        |
| Polyamide 6,6 + 40% carbon fiber | 1340 | 280                      | 238                  | 21,0                        | 1,92                        |
| High strength steel  | 7806           | 1402                   | 210                  | 18                          | 2,7                         |
| Titanium alloy       | 4430           | 1002                   | 110                  | 28                          | 2,5                         |
| Aluminium alloy      | 2710           | 503                    | 75                   | 18                          | 2,7                         |

As can be seen from the table, with relatively close values of the density of composite materials, tensile strength varies from 82.6 MPa in polyamide to 1926 MPa in fiberglass, thereby approaching the values of steel. Young's modulus values also vary over a wide range - from 28 GPa for polyamide to 238 GPa for carbon fiber polyamide compound; and the specific modulus and strength of glass and carbon fiber can be several times higher than those of steel and titanium alloy. Compounds of a mixture of polyamide with carbon fiber are deformed under load less than high-strength steel.

Thus, some metal and steel elements in the structures can be replaced with carbon-, fiberglass and composites based on them, depending on the purpose and current loads.
However, it is worth noting that composite materials cannot completely displace steel from the construction market, as they are fragile and have low elasticity. Moreover, the manufacture of composite materials is a high-tech production, and the effectiveness of the use of such materials is justified to a greater extent by low-rise construction [8] and the creation of small architectural forms.

The most important task in the manufacture of structures from such materials is to maintain the structure of the material with a filler uniformly distributed throughout the volume. Practical experience shows that this task is best handled by 3D printing by a 3D construction printer (figure 1) [25].

![Figure 1. Construction 3D printer.](image)

In 3D printing, the product (structure) is printed in layers, the direction of the fibers in the material structure remains chaotic in each layer, resulting in a material with the expected isotropy [3]. This simplifies the calculation methods for load-bearing structures manufactured in this way. This technology reduces the clarity of the separation of layers in the structure and the relative unevenness of the previous layer is filled in by the next one. High adhesive strength allows us to consider the composite material as a monolithic one.

The proposed IT technology is undoubtedly innovative and allows us to solve a number of actual construction tasks.

3D printing allows you to create complex structural elements without nodal connections, for example, a construction truss in a monolithic design with mounting units for equipment, mounting platforms for mounting various communications. It is possible to create coating elements (truss, beam, etc.) together with the column, which will greatly simplify the installation of building structures.

3D printing of dimensional structural products directly at the construction site cancels transportation and rigging. The technology of erecting a structure (building) using 3D printing is changing the qualifications of employees and the equipment used.

In this paper, we consider the manufacture of a dome design from glass and carbon fiber, built with the help of a construction 3D printer.

2. Theoretical part
The 3D printer diagram is shown in Figure 2 and consists of a rail portal with servomotors and laser coordinate correction.

Two components are fed into the printer head - a binder with a reinforcing glass or carbon filler and a hardener. Proportions are tracked by step servo motors. In the head, the components are mixed and
squeezed out by the screw from the nozzle, and the head moves in the given coordinates. A mixer is installed in the raw material tank to maintain consistency and pumps for supplying material to the head through hoses. The printer is controlled using a personal computer and related software.

3. The results of the experimental data
Figure 3 shows the dome, the frame of which is made using carbon fiber filler, and the panels are made of fiberglass. This design was erected in a single pass with alternate supply of material. The advantage of this technology is that various spatial structural forms can be created that are more labor-intensive in the traditional mode of construction; at the same time, additional properties are discovered: increasing the bearing capacity of structures, translucency, solidity, etc. Dome manufacturing (3D printing) was carried out at company «LaserKam» (Naberezhnye Chelny, Russia).

4. Conclusion
Thus, according to the results of this article we can conclude:
1. The composition of the composite material (matrix and fillers) can be selected depending on the purpose of the constructed element (structure) and the requirements for it.
2. Composite materials successfully prove themselves when creating structural elements (structures) using 3D printing.
3. The construction of a 3D construction printer can be modified to a specific order (for example, an additional filler hose is connected, etc.).
4. 3D-technologies make it possible to solve various complex construction problems: from erection and reconstruction of structures of buildings (buildings) from a small element to the whole object and simplify their construction in hard-to-reach places, be made in various architectural and decorative solutions.

Using a building 3D printer, one can quickly erect (replicate) typical projects of buildings and structures.
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