Possibilities of three-dimensional printing additive technologies application in construction

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Abstract. The article presents the results of a study on the using additive technologies in construction possibilities. A historical review of the development of automation of construction processes and 3D printing has been carried out. The main methods of using 3D printing in construction production, their advantages and disadvantages are considered. Two fundamentally different methods of manufacturing building structures using 3D printing are described: inkjet binder application and multilayer 3D extrusion printing. The main types of construction 3D printers are presented: portal 3D printers, 3D printers with a delta drive, crane-type printers and printers made on the principle of a "robotic arm". The main properties and features of building materials used for 3D printing. The viscosity, the possibility of pumping and the grain size of the aggregate were determined as the basic properties of the concrete mixture for 3D printing. Materials and principles of reinforcement of structures obtained by three-dimensional printing are also considered.

1 Introduction

The history of the development of automation of construction processes dates back to the 1950s. The earliest approaches focused on automating masonry processes. In 1904, John Thomas was granted a patent for a bricklaying machine in the USA (US Patent 772191, Thomas, John, "Brick Laying Machine", published 1904-10-11). In the 1960s the development of automated construction technologies using pumped concrete and isocyanate foam began. The development of automated construction of buildings using sliding molding methods and robotic assembly of components was first introduced in Japan to ensure the safety of the construction of high-rise buildings by Shimizu and Hitachi in the 1980s and 1990s.

Three-dimensional printing processes (hereinafter 3D printing) were first developed in the 1980s for photopolymers and thermoplastics. For some time, 3D printing technology has been limited to certain industries (aerospace and biomedical industries) due to the high cost of the materials used. However, with the expansion of the knowledge base and the development of technologies in the field of 3D printing, additive manufacturing processes have been developed for other materials, including materials based on cement binders.

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Innovations in the automation of concreting processes continued throughout the 20th century.

3D printing technology from concrete was introduced at Rensselaer Polytechnic Institute in New York when Joseph Pegna first applied additive manufacturing to concrete mix in 1997. This experiment was a proof of concept in which Joseph Pegna recognized the developing robotics industry and saw in it an opportunity to automate the construction process, as well as reduce costs and waste [1]. Joseph Pegn's research would later become the basis for building 3D printing.

In 1998 Behrokh Khoshnevis from the University of Southern California developed the Contour Crafting system, which was based on the first device for multilayer concrete extrusion. The system used a computer-controlled crane to automate the pouring process and was able to create smooth contoured surfaces. Behrok Khoshnevis initially developed this system for the rapid construction of houses in the aftermath of natural disasters. He claimed that the system could complete the construction of a house in one day [2]. Thanks to innovations in the development of building materials, a variety of mixtures and printing technologies, researchers and engineers have since expanded the possibilities of construction 3D printing.

The first construction projects using this technology appeared only in 2014, when a Chinese company announced the construction of 10 houses per day. In Russia, so far, it was only about small architectural forms (benches, flower beds, fences). But already in 2017, the Russian startup Apis Cor printed a whole house in the Moscow region. Since then, news about new 3D-printed houses has been appearing periodically. However, despite the fact that the technology proved to be very promising in terms of the speed of housing construction and reduction of construction costs, no mass implementation followed.

2 Materials and methods

To date, a number of different approaches have been presented, which include the manufacture of building elements and structures in factory conditions or the construction of buildings in construction conditions using industrial robots and portal systems. Currently, two fundamentally different methods of manufacturing building structures using 3D printing are used for 3D printing: inkjet binder application and multilayer 3D extrusion printing.

One of the most unusual variants of construction 3D printing, developed by Italian engineer Enrico Dini, is a binder-based 3D printing technology, also known as powder-based and binder-based 3D printing. Before Joseph Pegna applied this system to concrete, the technology was originally developed at the Massachusetts Institute of Technology to activate starch or gypsum powder with water as a binder [3]. During inkjet application, the printhead selectively applies a liquid binder to the powdered base, layer by layer. The layer height usually varies from 0.2 to 2 mm and determines both the printing speed and the level of detail of the finished part. For inkjet application of the binder, post-processing is required after printing is completed. The unreacted powder must be removed mechanically using brushes and dust extraction equipment. Additional curing steps may also be required in furnaces with controlled humidity and temperature. Finally, coatings can be applied to the product to improve the surface qualities of the part. Typical materials used for coatings are polyester or epoxy resin [4].

The technology of 3D printing with concrete using inkjet binder printing was demonstrated by Enrico Dini using the "D-Shape" printer invented by him. Unlike competitive installations, the 3D printer "D-Shape" does not use an extruder positioned along three axes, but operates with an array of 300 nozzles mounted on a movable platform.

The technology is more like inkjet printing, and the array is used to apply a binding agent to layers of sand.

The first printer model, patented in 2006, printed with epoxy resins, but this approach caused a lot of technical difficulties and did not receive further development. The new version, patented in 2008, uses non-hydraulic Sorel cement based on sand activated by magnesium oxide in a powder layer and a liquid solution of magnesium chloride as a binder.

Compared to other 3D printing methods for architectural and construction applications, inkjet binder printing provides a higher degree of geometric freedom, including the ability to create unsupported consoles or projections and hollow parts. Unlike other 3D printing processes that require auxiliary support structures, binder inkjet processing relies on a layer of unbound powder to provide continuous support for successive layers during manufacture.

Theoretically, the technology allows you to achieve high printing speed, but in practice there are limitations due to the slow hardening of the material. It takes about one day to fully grasp. Typically, with 3D inkjet printing, the remaining powder can be reused to re-manufacture parts. However, the recyclability of cement powder and aggregate is problematic due to exposure to environmental humidity, which can trigger the hydration process. Therefore, inkjet 3D printing is not suitable for construction in building conditions.

Multilayer 3D extrusion printing is carried out by a special printhead equipped with a screw extruder and a hopper for the mixture. A special fine-grained mixture is fed into the hopper manually or by means of a pump and is squeezed out layer by layer onto a section of the structure according to the design documentation and the control program. The thickness of the layers is usually from 5 mm to several centimeters. An automatic grout tool can be attached to the extrusion nozzle, which aligns the layers and closes the grooves on the interlayer surfaces, resulting in a smooth concrete surface. The printing process also allows simultaneous installation of fittings and engineering communications. In most cases, multilayer 3D extrusion printing is used in construction conditions and is accompanied by the use of large-sized 3D printers.

Unlike the classical technology of manufacturing monolithic concrete structures and spraying, multilayer 3D extrusion printing does not require a formwork device. This can be considered as a significant advantage, since a significant share of resources is spent on the processes of the formwork device. The main problems of multilayer concrete extrusion are the specified rheology of concrete, the integration of reinforcement in the printing process and the formation of cold bridges at the interface between successive layers.

One of the most significant problems of extrusion printing is related to the vertical speed of construction. The concrete must be sufficiently mobile so that it can be lifted, squeezed out and mixed with the previously laid layer, at the same time it must withstand its own weight and the weight of the material to be subsequently laid. The formation of a cold seam should also be avoided, since its presence negatively affects the design characteristics and durability of the final product. From which it follows that there is a time limit between the laying of adjacent layers, which limits the spatial characteristics of the printed perimeter with the same properties of the concrete mixture [5].

Another 3D printing technology is the slip forming technology. Robotic slide molding, a process developed at ETH Zurich called "Smart Dynamic Casting", is sometimes included in the family of 3D concrete printing processes, along with layer-by-layer extrusion. This process roughly corresponds to the definition of 3D printing due to its additive nature, when the material is slowly extruded through an actuated mold that can change its cross-section. However, unlike other 3D printing processes, slip forming is a continuous process rather than discrete or layered, and therefore it is more closely related to molding processes such as casting and extrusion [6].

3 Results and discussion

Construction 3D printers are engineering devices that create structural elements of buildings, small architectural forms or whole buildings in layers. The principle of operation of construction 3D printers mainly consists in the extrusion (or extrusion) of a special mixture according to a given three-dimensional computer model, layer by layer. With its help, you can create individual building elements in factory conditions, as well as completely erect a building directly on the construction site. The extrusion method is the most common, though not the only one. Along with other methods, it has earned its popularity in the market due to its ease of operation and maintenance. Such devices allow you to print objects of almost any given shape, the production of which is impossible for conventional serial construction and using standard mixtures.

There are several main categories of robots that are used for 3D printing. Their choice depends on the scope of application, the scale of the project and the printing technology. The printers are used in combination with simulation software that loads building information directly into the printer. All construction 3D printers, as a rule, consist of a supporting structure and a printhead with a nozzle that squeezes out concrete. There are four main types of devices:

- **Portal 3D printers** – Portal robots are the most common in 3D concrete printing. According to the basic layout, it resembles a gantry crane, but instead of a hook on the cable, a truss with a printhead is used. This type of printer is called an XYZ printer, because when working, the print head moves along three mutually perpendicular axes. Structurally, such a printer consists of four racks at the corners of the construction site, on which the printer rises along the axis in the vertical direction along the Z axis, two supporting beams along which movement occurs in the horizontal plane along the X axis, and a portal beam along which the printer head moves along the Y axis.

Stepper motors are usually used as a drive, but servomotors with a large torque and feedback from the controller can also be used, which ensures high accuracy and uninterrupted operation. Such printers are capable of printing individual parts, small architectural forms, as well as small buildings as a whole, provided that they are placed under the printer portal.

The simplicity and reliability of the design, as well as the possibility of erecting a building directly on the site are important advantages of this equipment. The sizes of such printers can vary depending on the tasks, ranging from small shop models for printing products to large-scale printers for printing buildings. This type of printer is limited to vertical lift, but has high stability and ease of scaling for larger projects. Portal printers are always larger than the structure being built, which can increase the cost of transportation, installation and commissioning. The time-consuming assembly process limits the possibility of rapid movement. Nevertheless, they differ in the simplest control among other 3D printers;

- **3D printers with a delta drive** – delta printers are able to create more sophisticated objects when compared with XYZ devices. They are not tied to guides along coordinate axes. Such a printer is an inverted tripod consisting of three cables or rods on which the print head is held, and a high frame on which the motors controlling the supply of cables or rods are fixed. The printhead moves due to the synchronous change in the length of the cables, repeating the algorithm laid down in the software package according to the template. The disadvantage of the device is the limited space of the working area, as well as the time-consuming process of assembling the frame of this installation;

- **Crane type printers** – construction 3D printers operating in angular coordinates are automated devices resembling a tower crane. The inventor of the printer used the principle of a retractable construction crane, which is able to rotate around its axis and print an

object, being both next to it, that is, outside and inside the object. This approach made it possible to create a compact printer, thereby solving problems with the installation and transportation of equipment. Printers of this kind are capable of erecting structures that are much larger than the printer itself. The printer has small dimensions, therefore, the equipment is easy to place with the help of a crane both inside the building and outside, depending on the project of the building being erected. The disadvantage of the device is a limited area of operation, as a result, during the construction process it is necessary to resort to the help of auxiliary equipment to move the printer around the work area. Another disadvantage of the printer is its cost, which significantly exceeds the price of the portal device;

- **A robotic printer arm** based on an industrial manipulator is a constructive analogue of mechanical arms (manipulators that are used on assembly lines), consisting of several flexible joints that give them greater mobility. This type of printer has the largest number of degrees of freedom in 3D printing systems. Manipulator-based printers are also capable of applying concrete to surfaces, embedding components such as rebar, and performing any subsequent processing that may be required after the concrete has set. The advantage of such equipment is the small size and weight of the installation. Most often, manipulator printers are used for the manufacture of small-sized elements and structures. The disadvantage is the complexity and high manufacturability of printers, hence their high cost.

The material for 3D printing of buildings is a concrete mixture, but different from that used in traditional methods of manufacturing concrete structures. One of its key features is fine-grained. The main filler used in the material for three-dimensional printing is sand, which can make up more than half of the total volume of the dry mixture. The material for three-dimensional printing is most similar to a dry mortar mixture, similar to a dry plaster mixture. The main components of the material are: cement, which is used as a binder, sand, which is used as filler and a number of additives, which usually accounts for about 10-15% of the mixture. Additives play a key role in creating a material suitable for three-dimensional printing.

The printed material must have properties that can be controlled over a wide range of parameters in order to increase the efficiency of additive processes. The material for three-dimensional printing has three main properties: the possibility of extrusion, short flow time and strength. The possibility of extrusion is determined by the fact that the material has the ability to be easily and evenly squeezed out of the printing nozzle. There are three main factors affecting the possibility of extrusion:

- Viscosity is a state of thick semi–liquid consistency due to internal friction. In three-dimensional printing, the viscosity of the material primarily depends on the dosage of water. It is necessary to maintain a balance between a low-viscosity material that is too wet to support its own weight and a high-viscosity material that is too dry to allow the material to move through the concrete distribution lines of the printer.

Plasticizers and super plasticizers are common types of additives that can be used to reduce the viscosity of the solution while increasing its machinability, plasticity and productivity. Plasticizers are just one of many types of additives that allow a solution for three-dimensional printing to have lower water content while maintaining the same viscosity.

Most 3D printing solutions contain a patented composition of several different additives that interact with each other at the molecular level to achieve the desired characteristics. This creates a delicate balance when too much or too little of any one additive can have a significant impact on the overall characteristics of the material. Table 1 shows the main types of additives and the properties they impart to the concrete mixture.

Table 1. Additives to ensure the properties of the building mix for 3D printing in construction.

Properties of concrete mix	Component composition of additives
Acceleration of the hardening rate, increase in strength	Sodium aluminate, sodium silicate, sodium fluoride, potassium carbonate, calcium chloride, amorphous aluminum oxide, lithium carbonate, calcium formate, fine amorphous silica
Increased plasticity	Polycarboxylates, polyacrylates, melamine sulfonates, naphthalene sulfonates, lignosulfonates
Increased adhesion	Redispersible powders of copolymers of vinyl acetate, ethylene, acrylate, versate, vinillaurate and vinyl chloride, styrene butadiene, butylacrylate-styrene
Improvement of antifreeze properties	Carbamide, Potassium carbonate, Sodium formate, Calcium formate, Nitrite, Calcium nitrate
Disperse-reinforcing	Steel fiber, cellulose, polyamide, basalt, polypropylene, graphite fibers
Reduced thermal conductivity	Aluminosilicate and glass microspheres, foam glass, ceramic sand, polystyrene foam balls, expanded vermiculite, cellular concretes

Another property that affects the viscosity of the printed material is the thixotropy of the material. Thixotropy is the ability to reduce viscosity (liquefy) from mechanical action and increase the viscosity (thicken) at rest. For three-dimensional printing, this property is of great importance, since the material must have the ability to pass through the hose lines of the equipment under pressure, but at the time of leaving the extrusion nozzle and reducing the pressure, the material must retain its shape, must not settle or deform.

- **Pumpability** is the ability of the material to be mechanically pumped throughout the system without the use of manual labor. Various cementing materials, such as fly ash and silica, have a positive effect on the pumpability of concrete. In addition, dosing and mixing must be carried out accurately and adequately, otherwise there may be problems associated with pumping concrete;

- **The grain size of the filler** is characterized by the maximum grain size of the filler, which should not exceed a quarter of the diameter of the pump pipe.

The second essential characteristic of the material for three-dimensional printing is a short flow time. The flow time begins immediately after mixing the material with water and ends as soon as the material loses its fluidity and becomes rigid enough to withstand its own weight and the weight of the next layer of printing and is not deformed by gravity. Over time, the viscosity of the three-dimensional printing solution begins to increase with the loss of pasticity, but at the same time the material must provide sufficient cohesion to fully bind to the previous layer. It is necessary that the freely flowing material, coming out of the nozzle, quickly turns into a printed layer that can retain its shape and not deform under the influence of gravity. Due to the thixotropic properties of the material, the transition from being inside the hose lines under pressure to squeezing out the environment helps to make this abrupt transition possible.

The end of the feeding time marks the beginning of the setting time. The setting time begins after the material has already adhered to the adjacent layers and ends after the solution has completely lost its plasticity and has become completely hard to the touch. It is important that the setting begins as soon as possible after the material exits the nozzle, because each subsequent layer adds additional weight to the underlying layers, which will deform if the extrusion speed exceeds the setting speed. As soon as the setting time ends, the curing time begins.

The rate at which the setting occurs can be controlled using additives called accelerators. The accelerator is a catalyst that accelerates the chemical hydration process and thus the curing period begins earlier. Most solutions for three-dimensional printing contain some form of accelerator. The type and ratios of accelerators used can be adjusted to improve the performance of different climatic conditions, for different extrusion speeds and even for different types of structures. However, some accelerators can cause cracking, weaken the integrity of the cured materials, and others are capable of releasing chemicals that can cause corrosion of steel and damage fittings.

Another important factor that can affect the setting time of the solution is the ambient temperature at which printing is carried out. High temperatures increase the rate of hydration, setting and strength gain. At a lower temperature, the reverse process occurs. There are additives that can reduce the effect of temperature on the rate of hydration. These additives allow the printing solution to work well over a wider temperature range. But this is not a universal solution, especially at temperatures around 0°C. All cement-based concrete mortars must be protected from freezing until the minimum compressive strength is achieved. There are also additives that can allow the material to work well in freezing conditions.

When the setting time of the material ends, the curing time begins, but the curing process takes much longer. Most industrial concrete mixes have a seven-day curing period to achieve 70% compressive strength and a twenty-eight-day curing period after which they reach approximately 80% of their full compressive strength. For high-quality curing, favorable conditions must be provided: sufficient humidity, temperature and time for the material to achieve the desired properties. The duration of the curing time depends on five main factors: the formulation of the solution, the design strength, the size and shape of the three-dimensional printed element, the time of year and weather conditions, the conditions of future operation. The material for three-dimensional printing may contain special additives that control the speed at which water can evaporate from the material, with their help you can get rid of expensive and time-consuming procedures for concrete care.

Additive technologies of three-dimensional printing with concrete require appropriate technological concepts of methods of reinforcement of structures. The main reinforcement methods for 3D printing are the following:

- **External reinforcement**. The main area of application of the external reinforcement method is the production of reinforced concrete elements (beams, columns, etc.) using three-dimensional printing technology without the integration of reinforcement during printing. The implementation of this approach makes it possible to produce structural elements of complex shape, low weight and optimized shape. This approach is based on the idea that a beam made of reinforced concrete elements can be cut into several segments, which are printed separately, and at the second stage are assembled with a steel reinforcing system to create the final reinforced concrete element.

The technological strategy consists of printing several concrete segments, each of which is designed according to a specific mechanical model to withstand variable bending moments and shear forces. In addition to the printing stage, this approach requires that the segments be designed as a whole with the reinforcement system in order to correctly select the stretched reinforcement in the lower part of the beam and fix the segments into a single continuous element [7]. The reinforcement scheme adopted in the prototypes presented by D. Asprone et al. it consists of two separate external steel reinforcing layers installed on both sides of the beams connected to each other by means of threaded rods. The latter are located in the holes of each concrete segment and are fixed with a high-strength, low-viscosity cement mortar. The steel reinforcement of a flat reinforcement system is connected to a non-flat system using connectors with external threads and hex nuts;

- **Internal reinforcement with prestressed reinforcement.** When using prestressed internal reinforcement, solutions known from traditional prestressed structures, in particular prefabricated segment bridge structures, are used. Despite the similarity with the manufacturing process of external reinforcement elements studied at the University of Naples, this approach uses a different mechanical principle, since it is based on the fact that concrete remains in a state of compression all the time, and not on the combination of actions between concrete during compression and reinforcement during tension. Consequently, the design is based on a strategy to overcome the need to take into account tensile stresses. This can be achieved by designing compression-loaded structures, but the use of additional prestressing allows this strategy to be extended to elements that are usually associated with significant tensile stresses.

This principle of prestressing was first applied to the design and manufacture of a concrete bench by three-dimensional printing at Loughborough University, United Kingdom. The printed structure was designed to have a certain number of through channels, they were used to place after printing reinforcing rods with a diameter of 8 mm, which were pre-stretched and filled with cement mortar;

- Reinforcement of printed permanent formwork. In some projects, a different strategy was adopted, namely the use of three-dimensional printing as a permanent formwork for conventional reinforced concrete. In this case, the armature is placed during printing. Reinforcement using conventional steel elements is a simpler approach than the technologies described above. Manually placing horizontal and vertical reinforcing bars is one of the simplest solutions that can create a regular reinforcement scheme in structural elements with standard geometry. This approach has been combined with several three-dimensional printing methods currently available on the market. A typical example is the production of reinforced concrete walls using contour processing techniques, in which reinforcing ties are manually inserted between layers at intervals of 300 mm in the horizontal and 130 mm in the vertical direction, respectively. Despite the fact that this approach makes it easy and efficient to implement reinforcement, some limitations are significant from the point of view of structural design. This approach raises concerns about the interaction of printed and cast concrete, the control of the concrete coating and the effectiveness of the structure, as well as about the flexibility in terms of the possibilities of digital production of complex shapes. These aspects limit the range of applications to those structures that are characterized by simple loading conditions or those that do not require the manufacture of complex stable structures, such as vertical elements subjected to compression loads;

- **Fiber reinforcement.** To ensure the strength and rigidity of the structure without reinforcing concrete with steel reinforcement, it is possible to use fiber as a reinforcing component to improve the properties of the construction mixture for three-dimensional printing. Table 2 shows the main types of fiber and the main advantages of its use.

Fibrous reinforcement is a common additive in conventional concrete. Fiber is added to concrete mortars of any purpose to give strength, toughness, eliminate shrinkage and prevent cracking, increase durability and abrasion resistance. The fibers work well with traditional poured concrete, but based on the experience of foreign colleagues, they tend to bond with each other and create small defects and inconsistencies in three-dimensional printing. Fiber reinforcement can also affect the fluidity of the solution and make it difficult for highly viscous material to enter the hose lines, which can increase the likelihood of clogging. Adding fibers to the concrete mortar is an obvious solution strategy, which was investigated by B.Hambach and D.Volkmer [8], who added basalt, glass and carbon fibers 3-6 mm long to the printing mixture, as well as B.Panda et al. [9], who compared glass fibers of different lengths (3, 6 and 8 mm) and varied the volume percentage of fibers. Both studies reported a significant increase in flexural strength, as well as the influence of the

orientation of the fibers in the stacked mixture, but none of them discussed the effect on plasticity.

Table 2. Fiber types of used in combination with a building mix for three-dimensional printing.

Type of fiber	General property	Advantages
Glass	Compressive (tensile) and bending strength increases; Thermal stability increases; Construction time is shortened; Reduced material consumption; The degree of crack formation resistance increases	Impact resistance increases; High density and uniformity of reinforcement are achieved
Polypropylene		The plasticity of the cement mortar increases; The specific weight of the mixture decreases; The wear resistance of concrete structures increases; Increased water resistance and frost resistance
Basalt		It has electrical insulating properties; Fire is not supported; Environmental friendliness
Steel		Concreting thickness and weight are reduced without loss of bearing capacity; Increases resistance to dynamic loads; Waterproofing characteristics of structures are improved

4 Conclusions

Based on the above, the following conclusions can be drawn:

- Three-dimensional printing has quite broad prospects for use in construction, but the possibility of using this technology is due to a number of factors [10, 11, 12]. With the help of 3D printing technology, both individual building elements can be manufactured in the conditions of the workshop, and various buildings and structures can be erected in the conditions of the construction site.

- Currently, two fundamentally different methods of manufacturing building structures using 3D printing are used for 3D printing: inkjet binder application and multilayer 3D extrusion printing. Inkjet 3D printing is not suitable for construction in building conditions. One of the most significant problems of extrusion printing is related to the vertical speed of construction.

- There are several main categories of robots that are used for 3D printing.

Portal printers are always larger than the structure being built, which can increase the cost of transportation, installation and commissioning. The time-consuming assembly process limits the possibility of rapid movement. Nevertheless, they differ in the simplest control among other 3D printers. The simplicity and reliability of the design, as well as the possibility of erecting a building directly on the site are important advantages of this equipment.

The disadvantage of devices with a delta drive is the limited space of the working area, as well as the time-consuming process of assembling the frame of this installation.

The disadvantages of crane-type devices are a limited area of operation and its cost, which significantly exceeds the price of a portal device. Printers of this kind are capable of erecting structures that are much larger than the printer itself. The printer has small

dimensions, therefore, the equipment is easy to place with the help of a crane both inside the building and outside.

The advantage of the equipment operating on the principle of a "robotic arm" is the small size and weight of the installation. The disadvantage is the complexity and high manufacturability of printers, hence their high cost.

- The printing material must have properties that can be controlled over a wide range of parameters in order to increase the efficiency of additive processes. The material for three-dimensional printing has three main properties: extrudability, short flow time and strength.

- Additive technologies of three-dimensional printing with concrete require appropriate technological concepts of methods of reinforcement of structures.

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