

ADDITIVE TECHNOLOGIES IN CONSTRUCTION: SHIFTING THE PARADIGM OF BUILDING

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Abstract

Additive manufacturing is gaining importance in the building construction industry. With 3D printers for concrete or other materials, there have been significant advances in the material properties and technical excellence of the printed structures, which has enabled their huge expansion in the construction market. If properly embraced, additive manufacturing in the construction industry can bring about fundamental changes in structural design, crating safer, more efficient, economical, environmentally friendly and aesthetically attractive building elements and structures. Another application in the construction industry is in space construction. Here it has a major role in the use of autonomous site control on distant planes, which can be first tested, used and developed on Earth.

Keywords

3DCP, buildings, 3D printing, reinforcement, space

1 INTRODUCTION

People have always built dwellings, whether they were detached houses or settlements. During the second millennium, there have been continuous improvements in the layout, safety, energy efficiency and usability of these houses [1]. Within Central Europe, these buildings were often constructed of stone, wood or brick, with wooden roofing being common practice. For security reasons, some of these houses were built close to castles, which also served as residences for the nobility, providing protection for the population [2].

Over several centuries, houses in different parts of Europe began to be built in different architectural styles such as Baroque, Rococo, Classical and Renaissance [3]. In the 20th century, however, modern construction appeared, especially the so-called prefabricated houses [4]. At the beginning of the 21st century, emphasis was placed on energy stability and reducing the energy consumption of building [5].

Building technology has continuously evolved and improved over the centuries. From the construction of the Charles Bridge, when dams on the Vltava River were used, to simple lifting systems for handling heavy building elements and materials at heights. The Industrial Revolution in the early 20th century provided an important impetus for further refinement and adaptation of these construction technologies, which continued at a high-rate into the 21st century [6].

These are three main areas of technology within the construction industry: materials, machinery and manufacturing technology. Each of these areas has undergone its own evolution and addressed different challenges before becoming a safe standard. Currently, one of the new directions of technology development in the construction industry is called additive manufacturing, but many professionals and the public still do not associate safety technology with traditional materials such as concrete.

3D printing (3DP)

Additive manufacturing (AM) has become a key technology in recent years and has found applications in various industries around the world. In healthcare, AM has been used to create bone replacements [7], in engineering to produce prototypes, machine components and sensors [8], and has spread to the electrical industry, becoming an important part of many industries around the world. Ideas predating AM date back to the 20th century, when the growth and shaping of biological structures were investigated [9], laying the foundations for the idea of modelling shapes using mathematical rules. This concept was gradually developed, and in the 1980s Charles W. Hull came up with the use of UV light for vat curing [10]. The next direction in the development of this technology is 4D printing (4DP), which differs from 3-dimensional printing (3D printing; 3DP) in that it allows for structural, dimensional, and other changes [11].

3DP, stemming from AM, has continued to be refined over the decades and has introduced new printing methods and materials [12]. One example is the Fused Deposition Modelling (FDM) method, where the material, called filament, is dissolved and plasticised [13]. It is then applied layer by layer to the printing substrate, allowing the desired shapes to be created. This technology is suitable for materials with melting points in the range of 150–300 °C.

At the turn of the 20th century, new extruders for paste materials began to emerge, laying the groundwork for the creation of new and adapted “classical” materials for 3DP, including concrete mixes and environmentally friendly materials [14]. In 2004, AM began to make its way into the construction industry in the form of larger prototypes. Printing frames with dimensions of 5.4 m × 4.4 m and the ability to print up to 5.4 m [12], [15] began to be used. These technologies began to be used in laboratories in Italy, USA, China, South Africa, Denmark, Switzerland and other countries [16], [17], [18], [19].

In the Czech Republic, universities and private companies are involved in 3D concrete printing (3DCP). Fig. 1. shows, for example, the printing of a load-bearing parametric column at the Festival of Architecture 2023 in Brno. However, there is a need to prepare construction documents for the design of structural elements, to unify the testing of material composition in the laboratory and during construction, to design the technical equipment of buildings, such as the location of sanitary facilities and their distribution systems, to carry out thermal engineering assessments, and to overcome prejudices regarding the use of AM in construction. This paves the way for the construction of the buildings themselves and for the provision of site facilities, the design of buildings and the management of repairs and deficiencies.

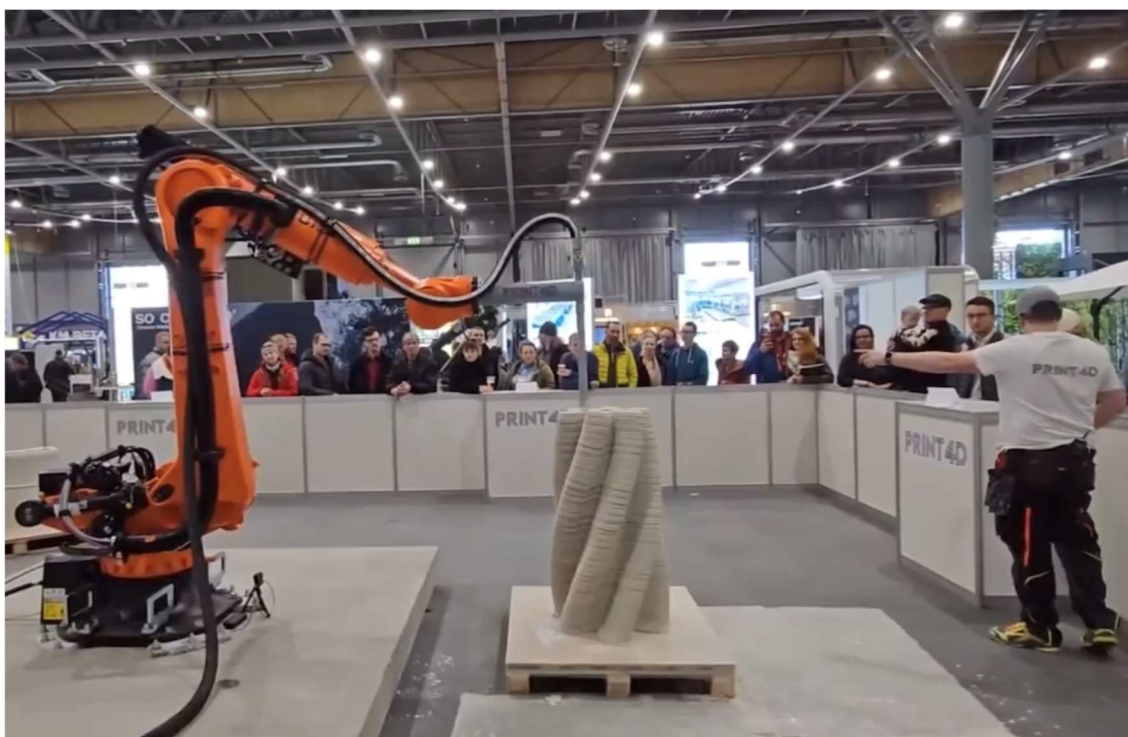


Fig. 1 Live 3DCP demonstration at the Festival of Architecture 2023 in Brno.

Material for 3DCP

The concrete mix for printing with a 3D printer or robotic arm consists of several main components that can either be mixed on site or prepared at the concrete plant. Quality control of this concrete mix is important because the materials supplied from the concrete batching plant on site will vary across the country and the world, and it is important to ensure that the mix meets the requirements of the specific project. This quality control should begin at the design of the building or structural elements when the concrete mix requirements are determined.

According to the literature Dey D. et al. [20] distinguish between the basic components of conventional concrete and 3DCP concrete. Conventional concrete includes binder (13%), water (27%), fine aggregate (23%), coarse aggregate (29%) and air spaces (3%). On the other hand, concrete is designed for 3DCP, and it includes basic materials such as binder (29%), water (24%), fine aggregate (39%) and air spaces (8%) [21]. Accelerating additives are also usually added for 3DCP concrete to speed up the setting, hardening and other chemical reactions, which is important for 3DP printing of concrete structures.

Manufacturing of 3DCP construction

The production of structural elements and parts using 3D concrete printing technology is based on the X, Y and Z coordinate system. The print head moves in the X and Y coordinate plane and successively prints individual layers of concrete. The Z coordinate determines the height of the product as each layer is formed. The X axis determines the direction of printing, the Y axis is perpendicular to the direction of printing and the Z axis remains the height axis [22], [23].

There are several different methods of 3D printing concrete structures and parts, including methods performed using robotic arms, large format frame printers, special cranes adapted for brick block placement, or printers on rail travel [24]. These methods are applicable for both indoor and outdoor applications (in-site printing) [25].

When creating concrete structures, it is important to choose a suitable material, for example Sikacrete-751 3D [26] precast concrete mix. The method of production depends on the nozzle (extruder) used, which may or may not be able to control the material flow [24]. The design hardware can be further modified by software that controls the print speed, the rotation of the extruder and the addition of accelerating components to the material [27]. This software is also used to divide the whole object into "slices" and to modify the printing path [28].

3D printing of concrete structures and parts is a demanding discipline, and problems such as print breaks caused by too many accelerators, inappropriate aggregate fraction or unwashed conveying hoses can arise. Maintenance of the technology is a key to successful operation. However, the technology is significant and has many potential applications.

2 APPLICATIONS IN CIVIL ENGINEERING

Vertical load-bearing structures

Vertical load-bearing structures include all wall and column elements that are perpendicular or partially perpendicular to the Z-axis, i.e. the vertical axis. The 3DCP method is mainly used for the manufacture of these structural elements. When comparing 3DCP structures with "classical" manufacturing methods, such as brickwork, timber elements or concrete elements [29], [30], emphasis should be placed on speed of construction, assessment of load-bearing capacity and reliability, meeting thermal engineering requirements, environmental impact and different printing options.

When printing vertical load-bearing structures, certain problems arise due to the length of the perimeter and the increasing height of the element. With a short perimeter and high height, there is a risk of elastic collapse of the upper part, where the lower edge may collapse under the weight of the new material [31]. At longer circumferences and constant print speeds, elastic collapse may occur from insufficient stiffness and slenderness of the printed trace. This problem is typical of single-track printing. The problem of wall slenderness can be addressed by adding steel or plastic profiles to increase stiffness and prevent collapse due to the large buckling length [32]. Another option is to use a second track or adjust the print speed and add accelerators. However, this procedure may affect the adhesion between the layers.

The main difference in creating vertical load-bearing structures is the variability in design, as opposed to methods that use masonry blocks, timber or reinforced concrete elements [33]. Standard methods for thermal engineering of these structures have been known and used for many years. 3DP structures have a specific shape, which complicates the application of classical calculation models for thermal transmittance. Some 3DP structures are reinforced with sinusoidal layers or steel anchors, which can create significant thermal bridges, especially when the temperature differences between indoor and outdoor environments are significant [34].

3D printing of concrete structures for vertical load bearing elements is possible but requires careful design with attention to thermal engineering properties, load bearing and reliability of the structural elements and suitability for the building [35]. Additive technologies are suitable for vertical load-bearing structural elements and offer interior variability. However, it is important to follow the methodological guidelines that will be available in the future.

Horizontal load-bearing structures

Horizontal load-bearing structures include beam, slab, slab-on-grade and coupled-type floor structures, lintels and other elements that serve to transfer the loads imposed on the horizontal structure to the supports, which are usually vertical load-bearing structures.

The 3DCP currently uses concrete mixes that have low tensile strength. This limits their use in horizontal support structures and the printing of these structures on site is still limited and not that common. There are two

main categories within 3DCP horizontal structures. The first involves the risk of sub-elements that are sequentially assembled and joined to form the overall structure [36]. The second category involves printing full-size structures [37].

All of these structural elements can be optimized for weight reduction and efficient material use using finite element analysis (FEA). Structures can be progressively lightened and strengthened based on the results of these analyses. These analyses have been successfully tested on beams that were first fully concreted and then optimized by FEA using stress-strain curves, leading to the design of printable floor-bearing lightweight elements [38].

Although the representation of 3DCP horizontal load bearing structures in the world remains limited, research and experimentation on their implementation is ongoing. For example, roof structures in the form of trusses have been investigated and have found applications in bridge structures where they are often prestressed [39], [40].

Foundation structures

Foundation structures have the task of transferring forces from the vertical bearing structures to the soil and it is important that they have as large a surface area as possible for the transfer of forces, allowing these forces to be distributed evenly across the foundation joint. At the same time, it is important to ensure that the bearing capacity of the soil is not exceeded. The basic elements that are used for the foundation of buildings include concrete strips, footings and piles.

AM 3DCP is usually not very suitable for these types of structures. However, the parametric design of the building should take into account the possibility of rounding of the foundation structures. For example, in the literature Wang L. et al. [41] have been printed structures that could have potential use in foundation structures. Reinforcing steel elements in the form of reinforcing baskets were placed in these structures and then concreted with commercial concrete mix to monolithize the structures.

Due to the variations possible in the vertical support structures, 3DCP formwork can be created into which the reinforcement basket can be inserted, or plain concrete can be retained. The substructure must be formed on a solid and clean substrate or on a reinforced substrate so that it can be printed on site. Another possible solution for foundation structures is to print a single perimeter, using a gyroid type geometry as fill to transfer the load to the foundation joint. However, this would require very detailed print and strength analyses to make this structure safe and reliable.

Stairs structures

Staircase structures are usually used to overcome height differences and can be made from a variety of conventional materials such as timber, steel, reinforced concrete, and can also make use of slab materials such as cement fibre boards [42]. The design of stair structures focuses on their load-bearing capacity, reliability, fire resistance and aesthetic appearance of the staircase.

The use of 3DCP stairs and their parts is not yet common in the world. For example, pockets have been created in wall structures, into which wooden elements are subsequently placed [43]. The 3DCP staircases created so far consist of individual stair arms and adjacent parts such as intermediate landings and landings. There is no mention of their experimental testing yet.

The advantage of such stair structures will be their variability, similar to all 3DCP structures. However, this option will require an FEA to be performed for all structural elements. The first staircases will have to be made full-size and tested according to ČSN 73 2030 [44], with an assumed load of 3 kN/m², which corresponds to the recommendation in the literature Pěňčík J. et al. [45]. This will serve to validate and correlate the results. Another advantage of 3DCP stair structures will be the subtler construction from large concrete staircases, leading to a lighter construction compared to traditional reinforced concrete staircases. Consideration can also be given to creating a staircase with a single printed perimeter, where the inner section is poured with a concrete mix and will contain reinforcing reinforcement rebar.

3 REINFORCING OF 3DCP CONSTRUCTIONS

Short fibres

While the interest in 3DCP structures has increased globally and the technology is applicable to some structures, which is appropriate, the reinforcement of these structures remains a partial taboo. Most of the reinforcement in 3DCP has focused on the use of discrete and dispersed reinforcement in the adhesive portion of each layer.

These layers utilize cellulose, steel, carbon or polymer fibres, [19], [46] or direct fibre-containing blends. However, the addition of fibres to the material mass increases the issue of material behaviour in the feed tube and print head. Filament clumping can occur, and because of this, partial blockages can occur and consequently damage the print.

The filaments inserted between the layers were investigated by Ahmed Z. Y. et al. [47], where they used a self-developed print head that adds short filaments before covering the adhesion layer. The problem arises with this option due to the bonding with the base layer, into which these filaments do not fit. However, there is a clear increase in both the flexural tensile strength and the fracture energy that can be accommodated by the test element and subsequently by the structure itself. Adhesion tests such as tensile tests and shear tests have not been carried out.

Additional reinforcement

Reinforcing 3DCP structures with additional switches is effective. Anchor zones are created on the element, between which steel prestressing cables are placed to introduce prestressing into the structure. The additional prestressing is mainly carried out with high strength cables or tees. Structures can be prestressed in several ways.

The first way is to pre-tension the cable and then wrap it with a concrete material that encases the entire cable. This method is very unsuitable in terms of long-term prestressing and the required prestressing mechanism. The second method is an additional prestressing with free interlacing of the cable. The cable rests parabolically on the pushed part of the structure and is anchored into the anchor blocks when Saltet T. A. et al. [48] prestressed the cable-stayed cycleway using anchor zones. The whole system was assembled from smaller 3DCP structural elements. The third method is additional prestressing, where the elements are printed segmentally and a sleeve with allowable valves is inserted. The prestressing cable is then pulled through the channel, fixed in the anchor zones at the end of the elements and the prestressing takes place. After this operation, the grout is added [49].

Simultaneous reinforcement

The most effective method of reinforcement in 3DCP structures is by continuous laying of reinforcing wires or polymer cables during 3DP. The concept was first introduced in 2006 in which steel cables were used [50]. The stiffness of the cable itself was found to be of great importance during continuous printing. If the cable is very stiff, there will be large horizontal forces acting on the layers, whereby the wire or cable will be deformed, and hence very negative deformation of the samples will occur. If the stiffness of the continuous reinforcement is lower, twisting will occur during printing.

Both laboratory and site testing should be obtained. However, all specimens should be measured in acclimatized testing facilities. These conditions and tests, carried out by the team of Marchment T. et al. [51], who noted that the use of wire cables in the adhesive joint helped to increase the flexural tensile strength by 170–190%. Tests also suggested that the blanketing war effectively functioned as a functional continuous network, but the test specimens were only laboratory specimens.

The big question mark remains the use in practice, where the individual reinforcement methods are very specific and are formed on conventional beams. Also, the applicability to other shape options needs to be tested, as 3DCP models can be parametric and thus always have different sizes.

4 SPACE DEVELOPMENT

The development of the press on cosmic bodies means a revolution in the formation of autonomous structures outside the Earth. The main objective of this technology is to eliminate the need for human presence and transport of building material from our planet [52]. This leads to minimal use of resources and the creation of separate space buildings.

However, the key element in this process is the development of new materials that are resistant to the extreme conditions of the universe. These materials are carefully designed to meet specific conditions of a particular planet or space body, ensure printing efficiency and long-term durability [53].

In addition, ecological sustainability is a key factor. Buildings on cosmic bodies must be conceived with regard to their later recycling. This means that printing technology must go hand in hand with the possibility of dismantling and reuse of components, which ensures long-term sustainability of space projects [54].

The difference between printing on space bodies and printing on Earth lies mainly in the extreme conditions of the universe, such as vacuum, extreme temperatures and radiation. Printing on cosmic bodies requires innovative technical solutions and materials to withstand these effects, and this is a challenge for scientific development [55].

Various objects and structures such as residential modules, reconnaissance equipment, energy stations and many others have been designed on space bodies. These structures are carefully adapted to the needs and specific conditions of each space body and represent an important step towards the sustainable settlement of the universe and exploring new planets [56].

5 DISCUSSION

3DCP technology undoubtedly transforms the construction industry. It offers a number of advantages such as reducing construction time, cost savings and the ability to create complex and adapted construction. However, there are also challenges, including materials, structural integrity and the needs of standardized documents. These are currently unavailable. The possibility of instant application is an example of possible prints of urban furniture such as benches, tables, fountains and much more.

The big challenge will also recently be in the field of reinforcement of structures. The design used in the vertical design of the wall is best suited for the application of this new technology. However, the correct programme and experience of the technician, which carries out individual applications both on the construction site and in the laboratory, must always be secured. For horizontal or oblique structures, behaviour in the drawn area must be detected in detail and the necessary reinforcement must be designed to achieve the FE analysis that will be needed in the design phase. The behaviour of outdoor printing should be examined consistently, by which the detection of solar radiation, dustiness, unpredictable weather, humidity or air temperature should be achieved. All these factors will play significant rolls in designing structures.

After a certain time, the Earth will gradually lose its supplies for the living of the human population. Therefore, it will be necessary to build bases outside the ground. It would be advisable to build objects on these planets without autonomous management without the physical presence of a person, which could ensure just additive production.

6 CONCLUSION

3D printing of concrete structures (3DCP) and generally additive production (AM) are fascinating innovations found in civil engineering and construction. In recent years, considerable advances have been made in this area, which opens new possibilities in the design and construction of buildings. AM has become a key technology in various fields around the world, from creating bone compensation in healthcare to the production of prototypes and components in industry. The ideas and development of technology date back to the 20th century, and since then they have become the basis for modelling shapes using mathematical rules.

3DCP brings new options for creating concrete structures with speed and flexibility that have not yet been possible with traditional methods. However, this technology still faces several challenges, including reinforcement of construction and material quality control. Reinforcement can take place by short fibres, additional switching or simultaneous reinforcement during printing, each approach has its advantages and restrictions.

Despite technical challenges and restrictions, AM and 3DCP have a huge potential to change the way the buildings will be designed and built. There are many possibilities for creating new design elements and to achieve a more efficient and sustainable construction industry. However, it will be important to carry out further research and development in order to achieve the optimum use of this technology and ensure the safety and reliability of buildings created by 3DCP.

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