Additive Manufacturing for Construction

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Additive Manufacturing for Construction

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Foreword

The adoption of digital solutions in construction has been proved to increase work safety, and it supports the circular economy by reducing material waste and simplifying resource recapture. Additive manufacturing processes have the great advantage of being able to achieve flexibility in the geometry of the outcome. This characteristic makes additive manufacturing particularly suitable for constructing efficient forms that are difficult to create with conventional manufacturing techniques and results in a significant reduction in the quantity of material used. Such forms could be achieved through the use of novel algorithm-aided design (AAD) tools, which are already commonly used in other industrial sectors, such as automotive and aerospace industries.

The use of computational design to create new structural forms has been limited by the traditional building production process, which does not allow for freedom of design. Hence, the application of computational design tools to freeform design has often been limited to a few explorations in pioneering architectural applications. With the advent of additive manufacturing process in construction, the use of structural optimisation could potentially enable the realisation of a new generation of optimised structures. Current research efforts aim to combine additive manufacturing with optimisation tools to solve issues related to manufacturing processes (such as overhang) or exploit anisotropy in materials to find new optimal solutions.

The application of both additive manufacturing solutions and computational design tools for steel structures has always been limited to a few pioneering cases. Recent developments in additive manufacturing processes in construction have seen the application of these techniques to realise a new generation of structures in concrete, polymers and metals.

Concrete is both a low-energy and versatile construction material. One of its main advantages is that it can be casted on site. The casting techniques currently in use have evolved over the years, but there has been little change in over a century. Concrete structures are created using formwork, which bears the force exerted by the lateral pressure of the material before it achieves its initial strength. Once the formwork has been removed, concrete retains its shape, and its strength slowly continues to increase for 28 days. In the conventional method of forming, the formwork used in concrete construction is rectilinear, as dictated by the ease of assembly. This often limits the shapes of the structural elements to rectangular or other regular shapes. The limits imposed by the formwork often result in inefficient structural elements, in that they are heavier than they need to be and so use excessive quantities of material. This limitation has also translated into the way concrete structural elements are conceived and designed. More efficient structural shapes and forms, which provide the same level of structural performance in terms of strength and stiffness, can be achieved using less material. These shapes, however, cannot be produced using the conventional methods currently in use. Complex shapes provide the next level of structural performance and reduced material usage, but these require the use of form-free methods of production.

A paradigm shift is therefore required in the way that structural elements are conceived. To deliver shapes that provide the required performance and reduce usage of material requires technology for forming the complex shapes. Emerging technologies such as additive manufacturing and 3D printing of concrete play a vital role in this endeavour; however, they require integration with new sustainable materials, with modified rheology to make them amenable for 3D printing. The primary benefit of additive manufacturing technologies is the ability to manufacture parts directly from computer-aided design (CAD) data in a single step (Vaezi and Chua, 2011). Furthermore, by eliminating the need for formwork, 3D printing, for instance, might cut the cost of concrete buildings by 35–60% (Lloret *et al.*, 2015).

Concerning production costs, construction enterprises encounter various and significant difficulties. For example, casting concrete in situ generates a lot of waste material that must be removed later, especially if formwork is not reusable material. The use of reusable moulds does, however, cause less waste, making them more cost-effective, but a lengthy moulding process must be used in their production (Delgado Camacho *et al.*, 2018). Another concern about the environmental impact of moulds is their life cycle, especially when taking greenhouse gas emissions into account. The new technologies enable better fabrication, more accurate element production and the printing of any shapes that are challenging to manufacture for conventional applications, such as façade components (Buswell *et al*., 2007; Shakor *et al*., 2019).

In general, additive manufacturing using concrete has much more stringent requirements in terms of material control than ordinary concrete construction methods. In Chapter 1, Panda and Santhanam discuss the specific material challenges and development strategies for new sustainable materials, with controlled rheology, for use in extrusion-based concrete printing. One of the salient issues is how a material's fresh properties affect both its stability during printing and its final performance. However, concrete is not the only material to be used in construction; 3D printing of steel is another possible technology, as explained in Chapter 4.

Regarding applications for steel structures, the capabilities of the most developed metal additive manufacturing technology, powder bed fusion (PBF), have often limited the maximum dimension of the printed outcomes. Thus, it has been used to fabricate ad hoc connections, parametrically designed either for structural optimisation purposes or to create freeform gridshells. However, due to the intrinsic geometrical constraints of the printer environment (enclosed in a box with, typically, 250 mm sides), the application of PBF is limited to the fabrication of small-sized connections and structural details. More recently, directed-energy deposition (DED) techniques, such as wire and arc additive manufacturing (WAAM), have allowed the dimensions of the printed objects to be increased to several metres in span, thus increasing the potential use of digital fabrication in steel construction. The first application of this technique was MX3D's Smart Bridge, the world's first steel 3D-printed footbridge, located in Amsterdam's city centre.

The aim of this book is to present an overview of the 3D printing or additive manufacturing technologies most commonly applied in the construction sector, from the perspectives of both academia and industry. Each chapter is dedicated to a particular additive manufacturing process, including both concrete-based and metal-based techniques. Finally, the conclusions and remarks in the final chapter provide insights into the advantages and drawbacks related to digitalisation of the construction process.

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Dr Biranchi Panda is an Assistant Professor at the Department of Mechanical Engineering, Indian Institute of Technology (IIT) Guwahati, India. He is an early-career researcher specialising in extrusion-based 3D printing, with a special focus on material rheology, process modelling and optimisation. Dr Panda received his PhD from Singapore Centre for 3D Printing, Nanyang Technological University (NTU), Singapore, and joined IIT to continue his research, focusing on sustainable resources for additive manufacturing (SReAM). His research strives to develop printable low-carbon concrete by using novel waste materials. In addition to his strong contribution to construction materials, Dr Panda also brings research benefits in terms of developing mechanical systems and process automation for construction applications, which is his distinct and unique expertise. He mentors 15 PhD and six postgraduate students in their research projects on concrete materials. Dr Panda holds associate editor positions for the Elsevier journal *Additive Manufacturing* (IF: 11.63) and the ASCE's *Journal of Materials in Civil Engineering* (IF: 3.6), and serves as an editorial board member for *Nature Scientific Reports*, *Results in Engineering*, *Additive Manufacturing Letters*, *Rapid Prototyping Journal* and *Materials Circular Economy.*

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Chapter 1
Concrete additive manufacturing

Additive manufacturing using concrete extrusion

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Introduction

For many years, construction has been a slow and segmented process, as conventional construction methods generally involve several stages. For example, the construction of a concrete component involves installing formwork, pouring the concrete, waiting for the concrete to harden and then removing the formwork, which must be repeated for every construction component. The introduction of additive manufacturing, also termed three-dimensional concrete printing (3DCP), to construction is gaining a lot of attention, from both academia and industry, as it holds the potential to create a structure without the use of formwork. Other potential advantages of 3DCP include reduced human involvement, minimal material wastage and opportunities for mass customisation.

In extrusion printing, the extruded material is deposited in successive layers, as specified in the computer-aided design (CAD) model (Buswell *et al.*, 2018), in a similar way to fused deposition modelling. The main challenge is to develop a material that will retain its shape after extrusion and can hold the load of multiple overlying layers without deforming significantly. Contour crafting (CC), introduced by Khoshnevis in the mid-1990s in California, USA, was the first technology to use this extrusion process as a core fabrication method (Khoshnevis, 2004). The popular CC approach was introduced into construction practice by companies such as WinSun, TotalKustom and ApisCor, and was later termed 3DCP. The main challenge for extrusion-based concrete printing is to produce overhanging features without using any support material. When 3D printing with plastics, polymers or metamaterials, the deposited layer hardens rapidly, while in 3DCP and other concrete-based methods, the layers are in an in-between state, depending on the time since deposition and the material's setting time. The materials used in 3DCP tend to harden slowly because of the slow hydration reaction, which can also depend on the target part geometry, but hardening can be accelerated by chemical admixtures (Buswell *et al.*, 2020). The process of extrusion-based 3DCP can be accomplished by using either a robotic system or a gantry-based printer.

Robotic concrete printing

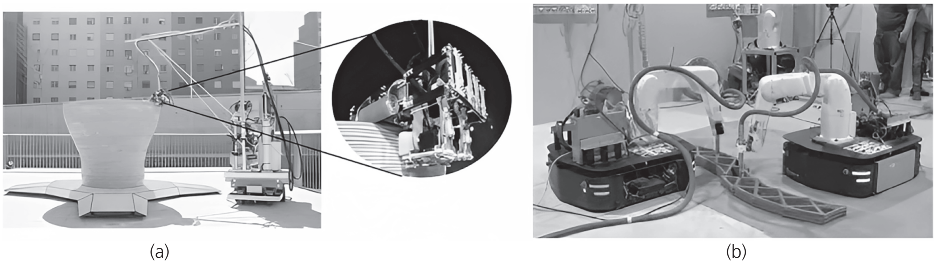
This uses a robotic arm that has a high degree of freedom to print complex components. The advantage of a robotic printer is that it can be used for 3D printing on temporary curved surfaces and for topologically optimised structures. Instead of using a single, large robot, the Institute of Advanced Architecture of Catalonia (IAAC) in 2014 employed a group of small robots that can work together using internet of things (IoT)-based swarm technology (Figure 1.1(a)). Similar work has recently been reported by a team of researchers from Nanyang Technological University (NTU), Singapore, demonstrating the ability of large-scale concrete printing by a team of mobile robots (Figure 1.1(b)). Despite having a greater degree of freedom, robots were generally found to be less preferred for small-scale offsite printing than gantry systems, as the process needs repeated calibration at each new location (Dörfler *et al.*, 2019).

Gantry-based 3D printing

Gantry-based printers are completely different from robot-based systems. Here, a three-axis machine (Figure 1.2) with a special print head is commonly used, which can move freely in the three dimensions of the build volume and deposit material on a stationary build platform. Gantry-based printers are used more often than robotic systems, both in research and practice, because of the simpler operational steps and larger print volume (Gosselin *et al.*, 2016).

The 3DCP process (Figure 1.3) starts with the creation of a digital 3D model using any modelling software, such as AutoCAD or SolidWorks, saved in the STL format. The next step is slicing of the modelled object into two-dimensional layers, followed by path planning. The controller stores the information and sends commands for final 3D printing (Buswell *et al.*, 2020).

Figure 1.1 Robotic 3D printers: (a) Institute of Advanced Architecture of Catalonia, Spain (Dörfler *et al.*, 2019); (b) Nanyang Technological University, Singapore



(a) (b)

Figure 1.2 Concrete 3D printer at the Indian Institute of Technology (IIT) Guwahati, India: extruder unit, nozzle, system for G-code generation, controller unit

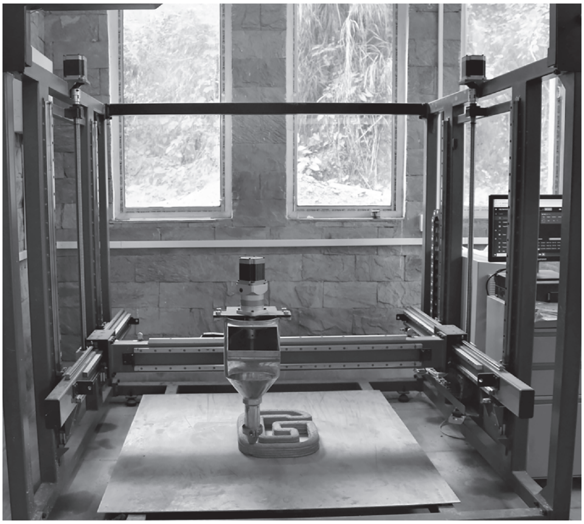
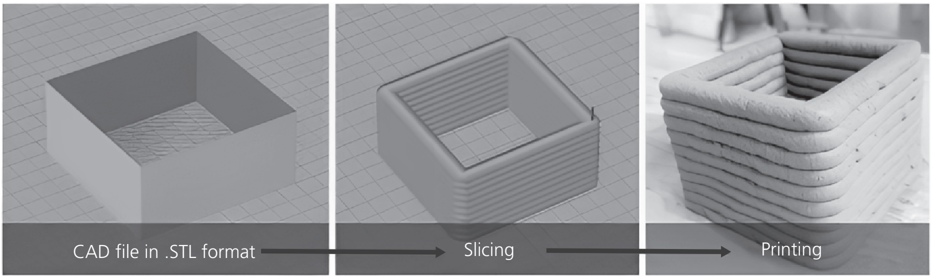


Figure 1.3 Summary of the 3DCP process



Material design based on rheology

Extrusion-based 3D printing of concrete requires the material to possess all of the following properties.

- The ability to be pushed or pumped through the concrete delivery system.
- Extrudability, or the ability to be extruded through the nozzle in a continuous stream without any breaks.
- Buildability, or the ability to maintain geometric stability in the lower layers when additional layers are being placed.
- Open time, or the ability to maintain the fresh state characteristics until determined amount of material is extruded and deposited.

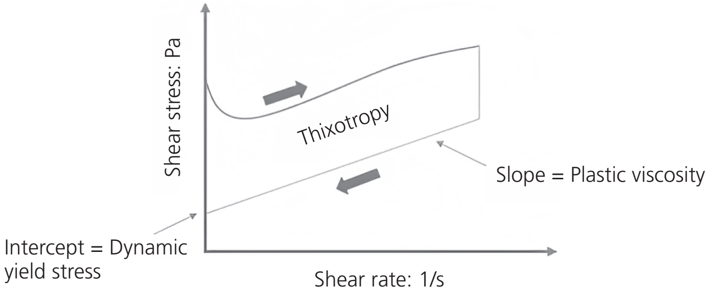
In order to satisfy the above four requirements, the mix proportion of the concrete involves selecting ingredients, such as cement, supplementary cementitious material, aggregate (usually of a fine nature), fillers, superplasticisers and viscosity modifiers that will produce a concrete mixture with the following characteristics.

- Uniform consistency or rheology, to enable smooth flow through the delivery system.
- Sufficient degree of cohesiveness, to prevent phase separation while travelling through the delivery system and through the nozzle.
- Thixotropy, so it can maintain the shape in which it is placed.
- Structural build-up, to ensure limited deformation of the lower layers when the subsequent layers get placed on top.

All the above characteristics can be controlled by fine-tuning the rheology of the cementitious mixture. Rheology refers to the flow behaviour exhibited by the material on the application of a (shear) stress. Materials such as water exhibit what is known as Newtonian behaviour, in which the material starts flowing with a constant viscosity as soon as shear is applied. In contrast, concrete belongs to a category of materials called yield stress fluids, in which the flow initiates only after a certain minimum threshold shear stress, called yield stress, is overcome (Banfill, 2006). Interestingly, there can be more than one type of yield stress for concrete. The static yield stress relates to the minimum shear to cause the material to flow from rest, while the dynamic yield stress relates to the minimum shear to make a ‘disturbed’ concrete flow again (in other words, to maintain flow after the breakdown of the internal structure), as shown schematically in Figure 1.4.

Figure 1.4 also depicts how the cementitious system shows thixotropic behaviour, which is indicated by the region between the shear ramp-up and ramp-down curves (Banfill, 2006). The greater the difference, the more thixotropic the concrete. In other words, a concrete exhibiting thixotropy will tend to maintain its geometrical shape when the shear is removed, but will show flowability when the shear is applied. In the case of extruded systems, this is important, as the shear is applied to the concrete to push it through the delivery system and through the nozzle, while once the extruded material is placed (at which time the shear rate is near zero), it is expected to stay in its intended shape in the location of the deposition.

Figure 1.4 Rheological behaviour of typical cementitious systems



The two principal rheological characteristics that define concrete behaviour are the yield stress and the plastic viscosity. While it is desirable for the viscosity of the material to be low, so as to allow the extrusion, the yield stress primarily governs the ability of the material to withstand the load due to the layers above. Further, as the material matures due to hydration, this yield stress continues to build up, leading to an increase in the resistance of the material to the additional stress caused by the subsequent layers.

These characteristics are brought about by the use of the following materials.

- *Cementitious material:* Typically, fly ash is used as a supplementary cementitious material along with ordinary cement. Fly ash particles, being spherical in shape, give better flow characteristics to the concrete and enable the production of workable concrete at low water contents. Further, fly ash also increases the paste volume because it is lighter than cement, and this increases the stability of the mix. In some cases, the use of silica fume in conjunction with cement and fly ash (Rahul *et al.*, 2019a) has been reported to result in better control of the flow properties, particularly in increasing the strength of fresh concrete.

  Substantial research has also been conducted on alternative cementitious systems involving alkali-activated cements (Kondepudi and Subramaniam, 2021; Panda *et al.*, 2018b) and special cements, such as calcium sulphoaluminate (CSA) cement (Khalil *et al.*, 2017; Kim *et al.*, 2020). Alkali-activated systems are advantageous from the viewpoint of active rheology control, which can be exercised by the choice of suitable alkaline activators. On the other hand, the use of CSA can bring about a rapid hardening of the 3D printable mixture, leading to excellent buildability. However, keeping such mixes workable for a longer time may involve the use of specialty chemicals, such as retarders (Marchon *et al.*, 2018).
- *Chemical additives:* A superplasticiser is absolutely essential for a 3D printable mixture, because it enables the production of concrete with the required consistency at low water content. The use of a compatible superplasticiser, particularly one from the polycarboxylic ether family of compounds, leads to an improvement in workability, which leads to better material delivery through the pipe system and the nozzle. The dosage of such chemicals needs to be carefully controlled to ensure that workability does not become so high as to cause a reduction in buildability. Often used in conjunction with a superplasticiser is a viscosity modifying agent (Rahul *et al.*, 2019a), which is tasked with a dual purpose of making the mixture more robust (i.e. stable against small changes in quantity and quality of other ingredients) and more thixotropic (i.e. with the ability to have internal structural build-up when at rest). Such chemicals are typically water soluble polysaccharides, such as methyl cellulose, and are typically seen in formulations of cementitious mortars. The one consideration while using a superplasticiser and a viscosity-modifying agent in combination is the expected level of retardation of the system. While the retardation is beneficial from the perspective of providing a larger open time, it may be detrimental to the buildability of the material. To improve buildability, accelerating admixtures are often added at the point of exit of the material (Bhattacherjee and Santhanam, 2022). The accelerators are typically based on aluminium sulphate chemistry, and are admixed just before the material comes out of the nozzle. An earlier addition of these compounds can cause the material to stiffen

inside the delivery system; hence, it is advantageous to alter the exit system to admix these compounds. The accelerated concrete that comes out of the nozzle is able to stiffen significantly faster than a mix without the accelerator, and leads to higher resistance to deformation after placement.

- *Graded particulate additions:* Usually, the use of aggregates larger than 5 mm, and in some cases 2 mm, is avoided for 3D printable concrete mixtures because the particle size heterogeneity makes it difficult to control the rheological characteristics of the material during this complex operation. While a few studies have attempted the use of aggregates of 8 mm or more in 3D printing (Mechtcherine *et al.*, 2019), such operations have often resulted in questionable finishes to the material. Therefore, in many of the large-scale examples, aggregates smaller than 5 mm are absent. It is often seen that 3D printable mixtures employ fine fillers to improve the stability of the mixture, usually inert materials such as quartz powder.
- *Other additives:* Research has shown that the use of fine particulate additives, such as silica fume or nano-clay, can also lead to substantial control of the rheology of 3D printable mixtures (Rahul *et al.*, 2019b). These ingredients tend to increase the cohesiveness of the cementitious systems, leading to improved rheological performance.

The type of the material delivery system usually determines the combination of materials that is used. In many instances, the use of a screw-based system to push the material towards the nozzle necessitates the use of a workable mix; that is, one that has low yield stress. In contrast, a system that uses a piston pump to push the concrete through the pipe can utilise mixtures that are stiffer. In such cases, providing low yield stress mixtures could lead to a danger of phase separation, depending on the amount of pressure applied by the pumping system. This necessitates additional tests on water retentivity to ensure the satisfactory performance of the concrete (Rahul *et al.*, 2020).

Mechanical properties and process–property relationship

This section describes the anisotropic behaviour of 3D-printed concrete, in terms of mechanical characteristics, and quantifies this behaviour using data from the literature. As illustrated in Figure 1.5(a), the orientations of extruded layers have been associated with the printing direction. It should be noted that the printed and cast specimens compared in this section were made using identical concrete mix proportions. The primary difference between specimens is the process of preparation, which is either casting or extrusion (Rehman and Kim, 2021).

Compressive strength

Figure 1.5(b) shows the loading directions in 3DCP, while Figure 1.6 shows the measured anisotropy in compressive strength with respect to the printing direction (C_c denotes cast concrete compressive strength and C_x, C_y, C_z denote printed concrete compressive strength measured along the x, y and z axes, respectively). Compressive strength readings along each axis were divided by the compressive strength of cast concrete to determine anisotropy, resulting in C_x/C_c, C_y/C_c and C_z/C_c, which indicate anisotropy in compressive strength along the x, y and z axes, respectively. In the literature, most comparisons of the compressive strength

Figure 1.5 Evaluation of anisotropic mechanical behaviour: (a) designation of *x*, *y* and *z* axes; (b) measurement of anisotropy in compressive strength

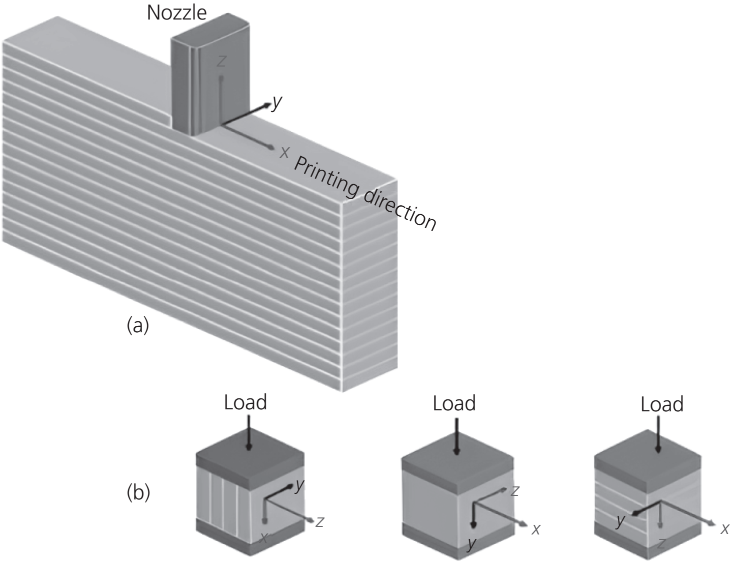
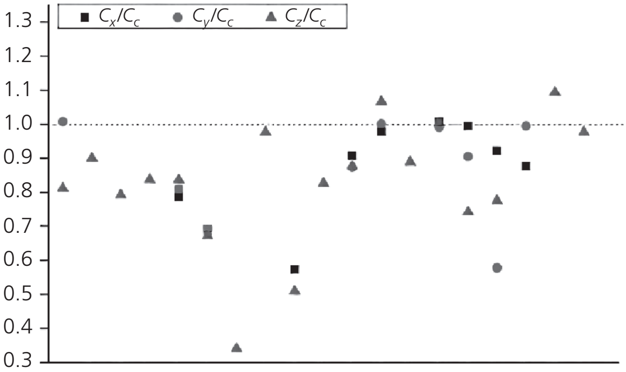


Figure 1.6 Anisotropy in compressive strength of 3D-printed concrete



of printed concrete and cast concrete show a lower compressive strength for printed concrete (Rahul *et al.*, 2019b). This implies that 3DCP results in concrete with lower compressive strength.

Flexural strength

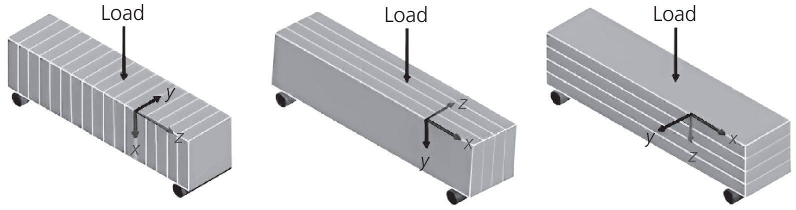
Figure 1.7 shows the loading direction in 3DCP, while Figure 1.8 shows the measured anisotropy in flexural strength (F_c denotes flexural strength of cast concrete, F_x, F_y and F_z denote flexural strengths measured along the x, y and z axes of printed concrete, respectively). A critical view of the data plotted in Figure 1.8 reveals two interesting pieces of evidence. First, the flexural strength of printed concrete along the x axis has been reported to be lower than that of cast concrete. Second, the flexural strength of printed concrete measured along the x axis has been reported lower than that measured along the y and z axes. This is due to the creation of tensile stresses between the extruded layers, at the interface, when flexural force is applied along the x axis. The interface is commonly the weakest point in 3DCP; it therefore cannot resist tensile stresses, resulting in lower flexural strength along the x axis. Figure 1.8 also indicates that the flexural strength of printed concrete measured along the y axis has been observed to be higher than that of cast concrete, except by Mechtcherine *et al.* (2019).

It has been found that fibre-containing printable mixes have always exhibited improved flexural strength along the z axis when compared with cast concrete. The increase in flexural performance of fibre-reinforced printable mixes has been associated with the alignment of the fibres along the printing direction at the extruding nozzle. Fibres prevent microcracks from developing into macrocracks and stitch together cracks in printed concrete parts, consequently increasing the flexural strength. The alignment of fibres is improved by using smaller-sized nozzles and higher dosage of fibres. Fibres close to the nozzle wall have more chance of being aligned with the printing direction than the fibres at the centre of the nozzle (Arunothayan *et al.*, 2020).

Effect of printing parameters on mechanical properties of 3DCP

In 3DCP, the printing parameters (time gap, printing speed, nozzle gap distance) influence the behaviour of the hardened printed concrete. The following subsections discuss the effects of these printing process parameters on the mechanical properties of printed concrete in the light of previously published research papers.

Figure 1.7 Designation of *x*, *y* and *z* axes for the measurement of the anisotropy in flexural strength of printed concrete



Load parallel to *x* axis Load parallel to *y* axis Load parallel to *z* axis