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Review

Biomimicry for 3D concrete printing: A review and perspective

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ABSTRACT

Three-dimensional concrete printing (3DCP) is an exciting new manufacturing paradigm for the construction industry. As this technology continues to grow and develop, it is revealing clear signs of progress towards industrial application with various global successes including the manufacturing of pedestrian bridges, houses, office buildings, emergency shelters and military structures. Much of the current research in this field is unsurprisingly focussed on improving and refining the technology for improved strength, reducing time and effort, and maintaining consistent quality, thereby ensuring reliability of the produced structures. Nevertheless, key aspects that have received significantly little attention thus far are the "design rules" for this new manufacturing technology. Novel manufacturing technologies bring along new design capabilities and possibilities, especially complexity in the case of additive manufacturing. This review paper aims to unravel the potential for complexity and, more specifically, bio-inspired design for 3D concrete printing. Three-dimensional concrete printing is ideally suited to take advantage of the numerous design principles from nature, to improve structural properties, minimize material usage and enhance the potential for structures manufactured by 3D concrete printing. We discuss all forms of biomimicry and bio-inspired design for 3D concrete printing – laying a foundation for future work to build on. Successful cases thus far are highlighted and the latent potential of combining bio-inspiration with 3D concrete printing is demonstrated. We hope this review paper stimulates further work towards bio-inspired 3D printed concrete structures with unique properties.

1. Introduction

Three-dimensional concrete printing (3DCP) is a form of additive manufacturing (AM) that is currently receiving much attention because of the viability of its use in the construction industry. The simplest and most widely used form of 3DCP is extrusion-based concrete printing: a layer-by-layer concrete extrusion process that allows the manufacturing of medium- to large-sized civil engineering structures such as single or multi-story houses, office buildings, pedestrian bridges and similar structures. Novel demonstrations of the technology are publicized regularly and at increasingly higher pace. To illustrate, four most recent examples are shown in Fig. 1, including (a) a military shelter printed in 36 h, (b) a double-story house, (c) the world's longest 3D-printed pedestrian bridge certified by the Guinness Book of Records and (d) a "future tree" pavilion shelter outside a company office.

The main advantages and potential of 3DCP lies in its ability to manufacture structures with minimal human input (automation) and in relatively short times. While the process is still more expensive than that required for traditional buildings, in addition to some structural integrity issues that require attention, 3DCP has a definite cost advantage when increased complexity or automation is required. Some of the first academic works describing 3DCP were reported almost 10 years ago [5, 6]. Multiple reviews of 3D concrete printing have been published since then and focus on various different topics in this field including the major challenges and potential [7,8], trends in the field [9], systems and technology used [10], the wider concept of digital concrete [11] and the

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Fig. 1. Recent examples of large-scale 3D-printed concrete structures [1–4].
Future Tree,2017-2019, Esslingen, Gramazio Kohler Research, ETH Zurich © Basler &Hofmann AG, Stefan Kubli.

underlying physics of the extrusion of cement-based materials [12]. Despite the successes achieved so far in realizing large-scale complex concrete structures [13], the huge potential of the design complexity available for producing concrete structures requires further investigation for 3DCP and clearly holds great promise. The shapes and forms of 3D-printed concrete structures typically have a curved and rounded organic appearance, and generally deviate from traditional design approaches. This is due to the additive manufacturing process, which is not only limited to traditional straight lines, but also gives AM structures a unique advantage in many applications. This has been utilized to great benefit already in metal AM, where industrial adoption is strongly driven by the capabilities of complexity to produce lighter parts with the same strength, to consolidate numerous parts into one-part design and the ability to add esthetic organic and biomimetic design aspects to the parts. This incorporation of bio-inspired and biomimetic design into AM parts was reviewed in detail for metal AM parts in [14]. The synergy between biomimicry and additive manufacturing has also been widely acknowledged and forms the basis for many new innovative solutions as discussed in [15,16].

In this present paper, we present a review and perspective of all forms of biomimicry and bio-inspired design specifically in the context of 3D concrete printing. This offers a view to the future, where the full complexity of this technology can be utilized in the construction industry.

2. The fundamentals of biomimicry

Biomimicry refers to the process of learning from and emulating nature in an attempt to solve engineering problems [17]. Although the term, or terminology, has only recently been established by Janine Benyus, biomimicry or bio-inspired engineering dates back to Leonardo da Vinci's early efforts to design bird-inspired ornithopters [18]. In modern science, the search for bio-inspired or biomimetic applications has become a true scientific discipline that has provided a fertile ground for a growing number of innovations [19]. Relevant to this review, architectural engineering has long drawn from nature as a source of inspiration [20]. To illustrate, the Gherkin Tower (London, England) mimics the lattice-like exoskeleton of the Venus' flower basket sponge (*Euplectella aspergillum*). The lattice design and round shape disperse stress resulting from the strong water currents experienced in the underwater environment, and in case of the Gherkin Tower, serve to reduce wind deflections. Another example is the Eastgate Center (Harare, Zimbabwe), which, instead of having air-conditioning or heating, regulates its temperature with a passive thermoregulation system inspired by mound-building African termites (*Macrotermes* sp.). A final example is represented by the Esplanade (Singapore, Republic of Singapore), whose main design consists of sunshades inspired by the spikes of the durian fruit (*Durio zibethinus*). By incorporating spikes, shading is provided, and overheating can be prevented – a particularly useful feature in a hot climate. These examples are shown in Fig. 2.

However, despite being popular, biomimicry encompasses a broad definition and is often used or understood incorrectly. As stated by Benyus: "a cork floor is not biomimicry, neither is using bacteria to clean water". Biomimicry should start at some tangible input from nature in the design or engineering process, either directly by emulation or indirectly by inspiration and through the use of generic concepts. Furthermore, some improvement should be gained by emulating nature – the primary purpose of biomimicry – yet not all biomimetic methodologies necessarily aim at solving engineering problems. Addressing (engineering) problems using a biomimetic approach remains problematic because of a lack of consistency of methods translating the biological principles into applications. Two aspects are important in this regard. Firstly, comprehensive knowledge of biology and life history of the study system used as inspiration should be the foundation of any biomimetic study, yet this is often ignored – biomimicry thus remains a mainly engineering-driven approach [21,22]. Secondly, from a more technical perspective, realistic designs or design rules should be made without concern for the structural complexity found in nature. It becomes clear that despite its increasing importance in research and society, the current biomimetic approach is due for a major revision [25]. Fortunately, the exponential rise in new technological advances has availed us new tools that have the potential to overcome some of the aforementioned hurdles associated with the current biomimetics approach.

Fig. 2. Examples of biomimicry and bio-inspiration applied in construction, (top left) Gherkin Tower based on the lattice-like exoskeleton of the Venus' flower basket sponge [26], (top right) Esplanade with durian-inspired roof spikes [26], (bottom) the Eastgate Center, inspired by the thermoregulatory behavior of termite mounds [23,27,28].

AM is an empowering technology that allows increasingly complex structures to be replicated with great precision, comparable to that of actual natural structures [14], allowing for the replication of biological material properties and functionalities – the aim of biomimicry. While the ability of AM for advancing biomimetic research has recently been reviewed by du Plessis et al. [14], the current paper provides a timely review of its implementation in 3DCP – a rapidly evolving field in AM – and aims to set a baseline for future biomimetic studies implementing the technique while taking into account the issues associated with the current biomimetics approach. Four categories of bio-inspired 3DCP will be addressed: biological inputs, inspiration and building blocks (Section 3), organic and freeform design (Section 4), structural/topology optimization (Section 5), and cellular design (Section 6). In addition, we address the current manufacturing limits and associated structural integrity issues of 3DCP briefly, highlighting areas requiring improvement for biomimetic design to be realized (Section 7),

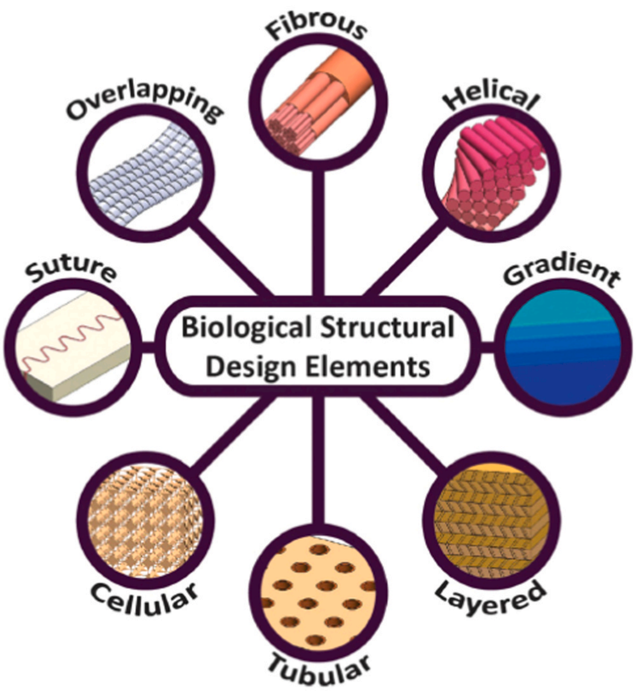

Fig. 3. Structural design elements from nature [31].

multi-functionality, an important aspect in bio-inspired design (Section 8), and conclude with bio-inspired materials themselves (including sustainable materials) in Section 9. In each section the biomimetic context is explained, and we highlight the potential and most efficient ways to make use of this for 3DCP.

3. Biological inputs, inspiration and building blocks

Biological inputs can take on numerous forms in structural engineering design, ranging from direct replication of the natural structures or designs based on a particular biological entity, to the use of generic design principles observed across various natural structures. Structural characterization is nowadays readily achieved using high-resolution 3D imaging, for example using X-ray tomography [29], whereas additive manufacturing, especially in polymer 3D printing, has taken on the lead role in replicating (natural) structures [30]. Despite the synergy between the two, one of the main hurdles to overcome is the inherent complexity of natural structures (also see Section 8) and consequently, the need to simplify designs for engineering application, for example, by taking inputs more generically. Natural structures are generally based on a limited number of repetitive structural design elements as outlined in [31] and shown in Fig. 3. These include fibrous, helical, gradient, layered, tubular, cellular, suture, and overlapping. Although each of these structural design units is present on a different length scale in nature, the principles behind them may be used to great benefit in engineered structures for improved performance. In 3D concrete printing, in particular, fibrous strategies have already been used with much success by fiber reinforcement using polymer and metal fibers entrained into the extruded concrete [32], or before or after extrusion using rebar. This improves the mechanical performance significantly and not only improves the buildability thereby allowing larger structures to be built faster, but also offers some improved overhang and complexity capability. Helical structures may be emulated in solid materials by changing the toolpath direction of the extruded material on each layer as demonstrated in [33], which is best for solid blocks and enhances the fracture resistance by inducing curved crack paths under fracture. Gradient structures (also called functionally graded materials) have

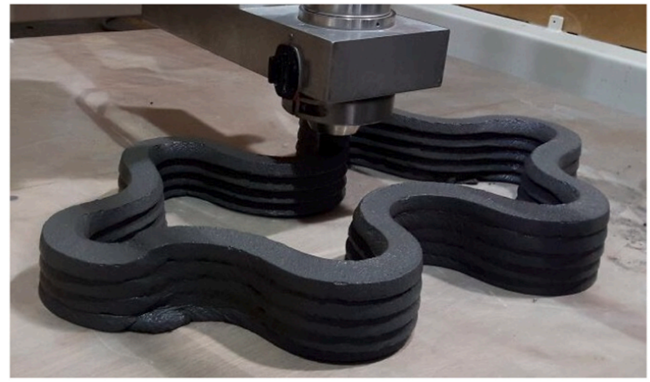

Fig. 4. Curved walls increase strength and buildability in 3D concrete printing, allowing more organic and freeform design possibilities.

been investigated widely in metal and polymer AM for improved and controlled fracture behavior, and tailored mechanical properties. Similar concepts have recently been investigated in gradient 3D-printed concrete, also using varying amounts of aggregate [34]. This was also demonstrated with multi-material optimization and the use of polystyrene for tailored performance [35]. The same concept may potentially be applied by varying the chemical content of the extruded concrete or by varied addition of reinforcement fibers, depending on the location of the extruder. Similarly, the layered strategy is inherently a part of the 3D printing process, but deeper insights into the layer thickness and wall thickness used in natural structures may provide keys to improved performance of these larger-scale structures (e.g., optimal layer thickness compared to wall thickness, which can be tuned by using different extruder heads or changing the toolpath extrusion strategy). The variation of the layer thickness depending on the loading condition has already begun to be studied for 3DCP as shown in [13] Cellular structures are discussed separately in a dedicated section below, due to their high potential and great success thus far in other areas of AM. Tubular, suture and overlapping concepts also hold keys to improving performance and require deeper insight into their relative sizes and orientations in natural structures for translation to 3DCP.

We highlight here the importance of identifying the structural design units that comprise natural structures and creating design rules with regards to how and where these are implemented at the organismal level, their functional/mechanical significance, and dimensions relative to the entire structure. These biomimicry concepts hold much promise for their application to 3DCP when utilized to improve the performance but require extensive experimental investigation and testing.

4. Organic and freeform design

Nature is a source of beauty – the organic shapes and freeform curves of natural structures often inspire similar structures in the arts and architecture. In fact, natural forms have inspired many efforts in bio-architecture [36]. Incorporating natural design elements and "green" concepts into engineering structures is often done for their esthetic value or perceived goodwill alone, without any structural or functional aims. However, rounded shapes and curves have some distinct structural advantages. The elimination of sharp tips and corners by using "fillets" (i.e., rounded corners and edges) allows benefits as they may reduce stress concentrations under loading conditions. This is already well-known in engineering design but is often added as a final touch in design, sometimes as a post-processing step in traditionally manufactured parts. In addition to rounded corners and tips, curved walls are a "natural" part of 3DCP bringing with it structural advantages. Curved walls – for example "crinkle crankle walls" were popular in the UK in the 1800s as they required less bricks, require no buttresses and, due to the curvature,

Fig. 5. Examples of topology optimized concrete structures [43,44].

were stronger against lateral forces [37]. This means that less material is needed for a curved wall compared to an equivalent-strength straight wall. This fits perfectly with the capabilities of extrusion-based 3D concrete printing. In fact, one of the problems with extrusion 3DCP is the difficulty in building along straight lines. Curved walls produced by 3DCP (example is shown in Fig. 4) were compared in detail with straight walls in recent experimental work reported in [38].

Another example of a direct benefit of curves is the well-known structural benefits of curved arches for doorways [39], which are not often used in modern buildings due to manufacturing costs for this type of complex design. As mentioned previously, 3DCP allows complexity such as this design style without adding cost.

The new capabilities of using curves and organic shapes in large scale structures include such forms as domes and arches, rounded and organic supporting beams and spider-web-like structures. There are, however, manufacturing limitations which are discussed in a later section – the main ones relating to overhang angles and minimum feature sizes, as well as anisotropy. But it is clear that a new architectural design and design-for-AM thinking is needed for 3DCP to fully utilize these curves and organic shapes within the manufacturing constraints. Design for additive manufacturing has been extensively investigated in traditional (metal and polymer) additive manufacturing [40], and similar methods will have to be used in 3DCP to overcome the manufacturing obstacles. The use of organic shapes and curves is therefore an inherent biomimetic design concept in 3DCP, which requires some refinement depending on the structure size, filament size and material properties to best make use of it.

5. Structural optimization

One key concept in nature is that material usage works on the principle of "just enough". Natural structures should not have excess material, as this will not only incur an unnecessary energetic cost but also add additional weight to its bearer, which, from a biological point-of-view, is often a non-optimal strategy (e.g., impaired locomotor performance in animals). This biomimetic concept has been incorporated successfully in simulation-driven (computational) design approaches, including the now popular topology optimization methods. This type of structural optimization, besides following the principle of "just enough" for its optimization, is also based on biological evolutionary optimization processes and is therefore inherently biomimetic despite lacking direct inputs from a natural system. The general idea is that expected loads and constraints are applied in a 3D simulation model, and material placement is optimized based on the simulation – regions of high stress require more material and regions of low stress require less. Repeated cycles of simulation and material placement optimization results in an optimal design. The output may require some smoothing and processing, but the result is a structure optimized for the loads expected, with minimal material use. This method is often used in metal additive manufacturing and shows great promise there, see for example [41,42]. It has also been applied to structural 3DCP examples in various projects to date, and some examples are shown in Fig. 5.

In addition to topology optimization, it is possible to make use of simulation to refine an existing design – a type of trade-off between traditional and simulation-driven design approaches. In this case, the

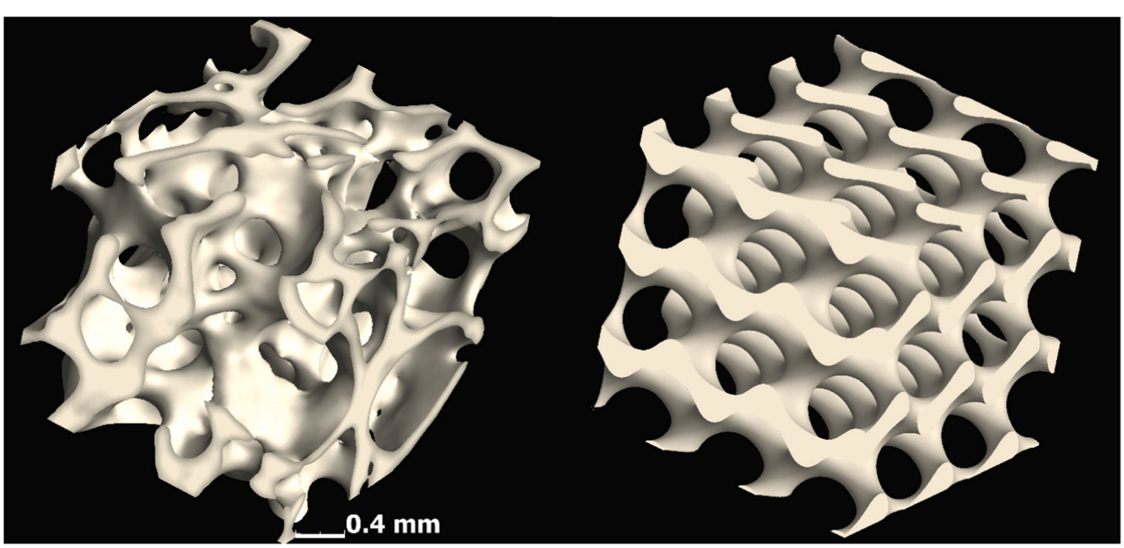

Fig. 6. Example of cellular structures – (a) trabecular bone CT scan showing a detailed natural cellular structure and (b) a designed gyroid lattice structure showing some similarity.

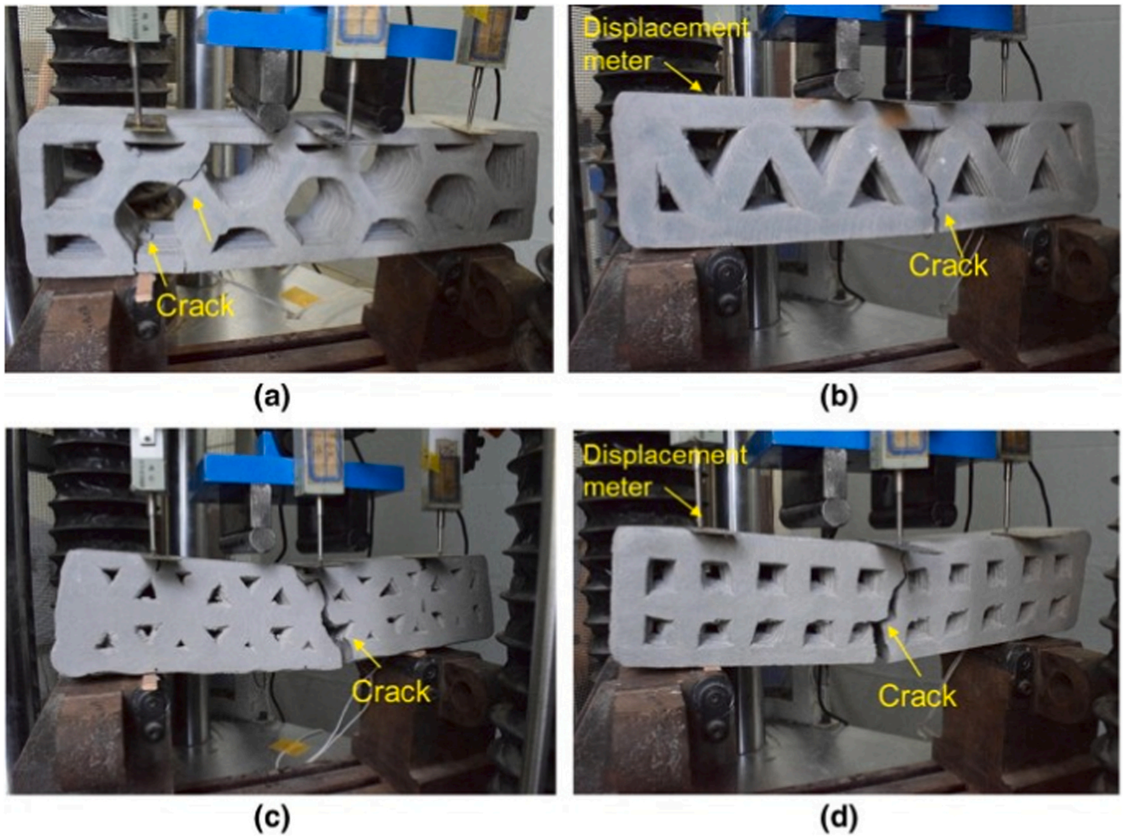

Fig. 7. Example of lattice structures in 2.5D printed concrete beams [62].

high-stress areas inform final finishing touches to remove stress concentrations and test sensitivity to variations in loads. Related to this is the concept of bio-enhanced engineering, which is described in [16]. In this case, a biologically-inspired structure is used for design inspiration to start with, but a combination of design and simulation tools are used to enhance the structure for the engineering application. In the case of 3DCP, this could include modifying the design to allow for manufacturing constraints.

Two of the most well-known algorithms developed for structural optimization are the bi-directional evolutionary structural optimization (BESO), and solid isotropic modeling with penalization (SIMP). The SIMP algorithm was first proposed by Bendsøe [45,46] to optimize structures with different design variables in a non-discrete solution. Later, this algorithm had been optimized by some researchers [47,48] towards a better design for generalized shape optimization with a higher volume fraction, in which the penalty factor remains a main feature of the algorithm. A concrete topology-optimized slab was developed with SIMP to reduce structure mass by 70% from the original solid concrete slab while having similar load-bearing capacity [49]. Another example includes a 3DCP 4 m-span girder with post-tensioning cable designed with SIMP algorithm, in which the volume of concrete is reduced by 20% compared to the original one and yielding a similar deflection [50]. The BESO algorithm is also known as a discrete method that redundant material is iteratively cleaned up from an object whilst the efficient part is added simultaneously. The method was utilized to optimize certain types of structures for either traditional manufacturing or additive manufacturing with shape optimization for underground openings [51], shell structure optimization [52], and topology optimization of 3D continuum structures. In recent research, a new BESO-based method has been proposed to address the critical overhang issue in additive manufacturing in general and 3D concrete printing, in particular [53]. Recent concurrent topology optimization of cellular materials is proposed to perform optimization at multiple scales [54,55]. In the concurrent topology optimization, the macrostructure is discretized with finite macro-elements/cells (microstructures) that need to be independently designed with finer meshes. These methods are all promising for structurally optimized and biomimetic concrete structures.

6. Cellular design

Cellular, porous structures are ubiquitous in nature, for example, in the shape of a beehive honeycomb and the cellular structure of wood and spongy bone (trabecular bone) with its interconnected networks of bone struts and plates (see Fig. 6, left), to name a few [56]. Manufactured cellular structures provide exceptional properties that can be modified and locally varied by design to provide unique responses. For these reasons they are widely studied for applications using additive manufacturing – in which case they are referred to as lattice structures – some properties include compliance, energy absorption, vibration isolation, impact absorption and blast protection [57,58], acoustic or sound absorption, thermal insulation or thermal control applications, to name a few. Reviews of additive manufacturing of lattice structures in polymers and metals are found in [56,59,60].

The basic mechanical properties of lattice structures are well-described by the Ashby-Gibson relationships for open cell foams [61]. The elastic modulus and strength depend primarily on the relative density of the cellular or lattice structure, always being a fraction of the bulk material modulus or strength.

Various ways of realizing large-scale lattice structures in concrete have been studied with some successes, as demonstrated in [63]. These include large-scale lattice structures produced by casting concrete into 3D printed sand molds, into complex fabric formwork by CNC machining, or into 3D printed clay formworks of large size. It was concluded that creating large-scale concrete lattices is a difficult task, but is technologically possible in various methods.

Fig. 8. Cast concrete lattice structures, produced by casting in plastic 3D-printed molds [64].

Extrusion-based 3D concrete printing works very well to create simple cellular structures in extruded 2D form – also called 2.5D (Fig. 7). These have many advantages and are simple to manufacture in 3DCP. They are typically used either for infill patterns in surface-closed beams (see Fig. 7) and walls, or for creating open-porous structures. When used as infill, an important advantage is the faster build rate, compared to fully dense structures of the same thickness. Creating more complex fully 3D cellular structures (as Fig. 6, for example) is still challenging for extrusion-based 3D printing of concrete, due to overhang problems. Nevertheless, there is some potential as some designs have less overhangs, and some designs may be modified to minimize overhang requirements, or some kind of (removable) support may be provided as discussed in [32]. Much progress in this area is expected in the near future as the capabilities of 3DCP are improved and extended by various ways, including the incorporation of fibers, etc.

Besides extrusion-based 3DCP, the possibility exists to create 3D-casted lattice structures, using molds from 3D-printed plastics. This was demonstrated by Nguyen-Van et al. [64], as shown in Fig. 8. Another concept realized recently was the use of 3D printed polymer lattice structures, infiltrated with high-performance concrete, to create a composite material with good strength and high ductility [65].

Some advantages of cellular designs in 3DCP are the faster build rates, less material use, thermal insulation when using infill patterns in walls (closed porous spaces), airflow allowing "breathing" structures or buildings when using open cellular designs, amongst others. The compliance of cellular structures may potentially benefit design against earthquake or disaster failures, but no dedicated study has been performed in this regard yet. Compliant structures with fibers allow very high elongation and layer-by-layer failure, which can prevent catastrophic failures under impact or high loading scenarios. These and other advantages of cellular concrete designs remain to be investigated in more detail and remain to be proven for large-scale concrete structures.

7. Structural integrity and manufacturing limitations

Despite all the potential and the recent boom in research efforts in 3DCP, it is still a developing technology with much structural integrity, process and materials issues that need to be solved. This places limits on the complexity and bio-inspired design that can be achieved reliably. This issue is key to biomimetic design and its implementation within safe limits. Structural integrity defines the safe design and assessment of a structural component under load at normal conditions, as well as when the load condition exceeds original design conditions. A number of current problems exist with the structural integrity of 3DCP structures which limit its potential for biomimicry and complexity; these are discussed below.

The first and most important issue is the strong anisotropic behavior (i.e., different properties in different directions), due to the layered structure and specifically due to inter-layer bonding which is weaker than other directions. This is unlike cast concrete, which is considered to have isotropic behavior [66,67]. This anisotropy and inter-layer bonding affect the compressive strength, flexural strength and tensile strength, in consideration of the direction of the applied load in the samples relative to the build direction (or the inter-layer direction).

Several researchers have investigated the compressive strength of 3D-printed cube samples, and varied results have been reported when compared with the mold-cast samples [66–69]. The varying strength of 3D-printed samples can be largely attributed to the interfacial bond strength of the different layers. It was reported that under the compression load, cracks are formed in the weak interfaces, which leads to lower strength of the 3D-printed samples [70]. Weak interfaces parallel to the loading directions may lead to splitting of track layers and thus premature failure of the samples. Lack of fusion between layers is widely reported and is likely the largest challenge in 3DCP, as discussed in detail in a recent review [71].

In addition to anisotropy and inter-layer bonding weakness, porosity influences the structural integrity. Porosity or voids are widely found in additively manufactured materials of all types and in various AM processes. These can influence the mechanical properties of the parts, acting as stress concentration sites and act as crack initiators [72]. For this reason, processes and materials are often optimized to minimize this porosity. In concrete materials, porosity is widespread and often found at levels of 1–5% or more [73]. However, the pores found in cast concrete are spherical and evenly distributed in the part. In 3DCP, due to the process of extrusion, the compactness of the materials may vary due to the layer by layer deposition. Thus, for the same mix, the density and entrapped air voids in the printed samples may differ significantly from that of traditionally mold-cast samples [24]. Voids may also form between the filaments or track layers due to the shape of the nozzle tip and the resulting shape of the track itself, and this can significantly reduce the density of the 3D-printed sample affecting mechanical properties [6,74]. The influence of different printing paths such as parallel and cross-hatch paths on the density and voids was also studied for 3D-printed cement paste material [75], where it was shown that the density and air voids in 3D-printed samples can be similar or even better than the mold-cast samples. The air voids in the interfacial zone (the connection between two layers) and intralayer zone (within a layer) were also studied in [68]. In comparison to the intralayer zone, air voids in the interfacial zone were found to be higher. Higher voids in the interfacial zone could lead to lower mechanical strength and may further influence anisotropy. Note that the measurement of voids in 3D-printed samples can be done by micro-computed tomography (μCT) scanning [73,76], using physical cross-sections and optical microscopy, or helium pycnometer, to name a few commonly used methods. MicroCT has also been shown to be useful for measurement of fibers inside concrete [77,78].

The influence of anisotropy of 3DCP cube samples collected from the curved and straight portions of a 3D-printed bench structure was examined by Le et al. [6]. About 30% lower compressive strength was found in the samples collected from the curved portion when compared with the mold-cast samples. For samples from the straight portion, this reduction was only a maximum of 15%. The strength reduction in the samples from the curved portion was attributed to the presence of a large volume of voids in the track layers in the curved region, which has implications for making use of curves (and hence for biomimetic design). The volume of material deposition in the inner and outer portion may not be the same, and thus more voids can form in the outer curved portion in comparison to the straight portion. This phenomenon was further proven in a study by Hambach & Volkmer [75] where higher strength was found for parallel shapes in comparison to the crosshatch shape. Nevertheless, little research is available on the anisotropic behavior of 3D-printed samples comparing straight and curved shapes and some optimization of the material deposition process or the material itself might be needed to address this effect.

The bond strength of the interface of 3D-printed samples with respect to the different printing parameters such as time gap, printing speed, nozzle stand-off distance, etc., has been investigated by many researchers. For the same material, Panda et al. [79] tested the influence of different time gaps (1, 5, 10, 15, and 20 mins) on the bond strength of 3D-printed mortar samples with two layers. A reduction of bond strength was found for longer time gaps. This behavior was attributed to moisture loss from the bottom layer: as this layer becomes drier over time; it absorbs more water from the freshly deposited layer. This water absorption can form some air voids, and this entrapped air at the interface can cause poor strength performance in the printed samples. The microstructural analysis also showed that the growth of hydration products might be delayed in the entrapped air voids due to the free calcium hydroxide in the voids [70]. This delay in the hydration may also lead to lower mechanical strength of the layer by layer 3D-printed samples. A similar result was found in a study by Van Der Putten et al. [80] where larger voids were found at higher printing speed and for longer time gaps, with a direct implication for compressive strength. A longer printing time gap produces cavities and voids not only in the interface but also in the track-layer [81].

For improving the inter-layer bond strength of 3D-printed mortar samples, Zareiyan & Khoshnevis [82] used a technique called interlocking where different sizes (0", 0.25", 0.50" and 0.75") grooves were created mechanically between the track layers. It was found that the samples with the interlocking size of 0.5" showed a 17% higher bond strength than the samples without any interlocking.

The complexity of design that is made possible by 3DCP technology is highly sought after by civil engineers, designers and architects – in the pursuit to realize complex structures beyond the traditional methods of construction. However, there are currently still manufacturing limitations to this new technology which need to be considered in the design phase [10]. One of the main limitations is constructing overhanging structures (currently limited to about 15°), which may require the help of some other support materials.

Another limitation is the requirement of the reinforcement in the 3D-printed structures. Three-dimensionally printed components are often faced with a lack of reinforcement such as rebar or fibers that can adapt to construction guidelines. Therefore, the research in building and construction should also move towards different methods to add reinforcement during or after printing. Some attempts have already been made to tackle this issue such as printing mesh, wire (steel or synthetic) with the concrete track-layer, and using fiber reinforcement concrete [135]. However, this may still limit the applications as well as the design span length of the printed structures as their volume is much less than the required reinforcement for a structure according to building codes.

Lastly, for concrete printing, no proper guidelines or standards are available, which may also limit the application of this new technology. It is clear from the literature survey that a considerable amount of research has been dedicated to studies considering concrete printing as a standard construction method. The adoption of concrete printing components in construction industries requires appropriate attention in terms of structural integrity and durability. This is not possible without any new standard or project code that allows appropriate experimental testing for validation. Different international working committees are working on this topic in order to recommend practical standards/guidelines for the widespread use of this technology. Proper guidelines should include the specific size of the printed samples for testing, and the minimum number of track-layers for objectively characterizing the mechanical and durability properties [10].

Some ways of overcoming the current design limitations are to manufacture 2.5D structures, as shown in Fig. 9, where the structure is built horizontally and turned upright. The incorporation of fibers and reinforcement allows a higher degree of complexity due to the

Fig. 9. Extrusion 3DCP printed in 2.5D and turned upright, with post-tensioning different parts for the final shelter. A 3D-printed bus stop shelter made by Chinese company WinSun Construction [89].

improvement of strength and further work in this direction is promising for opening the capabilities of bio-inspired design for 3DCP. Other solutions include the manufacture of complex parts and putting them together for the final structure, and also the use of formwork and shotcrete [88]. There have been very promising developments utilizing inline rheological control rather than the premix approach, for large-scale complex structures in 3D (moving away from 2.5D) as reported in [83–87]. Despite this progress, more research is needed in this direction to design materials and printing systems appropriate for 3D printing large-scale concrete structures with complex and biomimetic (over-hanging) designs.

At the same time, the name “concrete printing” is actually a misleading terminology as so far real concrete is not used. In most research studies, fine aggregates up to maximum 3 mm in size have been used due to the limitation of pumping by a mortar pump. Also, the ratio of the binder: aggregate is higher for all 3D printable mix designs compared with conventional casting mixes. Therefore, future research should target printing of concrete (up to 8 mm aggregate size) to avoid most commonly observed shrinkage issues due to higher fines contents in the 3D-printed mixes.

Skilled labor, cost of hardware and software, and scale of the printer could be other limitations of this technology in its current form of development. Unlike traditional concrete construction, here all the works from mixing to deposition are done automatically by the 3D printer and thus require skilled people for proper operation and implementation. In addition, the cost and the availability of hardware and software of the printer can be a major issue in some countries for adopting this technology. Finally, the scale of the printer, i.e., the dimensional limitation, could also limit the uses of this technology. Many of these problems can be addressed through continued research and development, and by appropriate knowledge sharing in this process.

8. Multi-functionality

One of the key aspects of biological structures is that they are seldom optimized to fulfill a single function. Most often, a natural structure is optimized to fulfill a variety of functions simultaneously, providing a solution that best fits multiple (sometimes conflicting) requirements. To illustrate, the body armor of animals not only serves to protect them against predators, but might also play an important role in thermoregulation. Armor plates with a high degree of vascularization (i.e., internal channels) might serve as thermal insulators, but comes at the cost of reduced strength, particularly impact resistance against sharp objects (e.g., teeth of predators) [90]. The aforementioned example does not represent an isolated case; instead, trade-offs are commonly observed in natural structures. As mentioned in Section 2, understanding the biology of the study system should always become a priority in biomimetic studies. Furthermore, once this information is available, bio-inspired multifunctional designs can be created, some of which would have been difficult or impossible to find by simulation methods.

Using simulation-based tools, as described in Section 5, is challenging in this regard. Still, future work may be able to optimize structures for load cases (stiffness with minimized mass) as well as other parameters such as thermal conductivity or permeability, simultaneously. In terms of construction and buildings, parameters often incorporated by architectural design may be possible through complex 3DCP design, including vibration and sound absorption, impact absorption and compliance to prevent catastrophic failures, as some examples. Incorporating electronics and sensors into AM produced parts has been a topic of some interest in metal and polymer AM [91,92], and this may hold particular advantages to construction. Incorporating sensors in key regions may allow structural health monitoring and contribute to improved long-term management of structures, using wireless connected devices, something key to the Industry 4.0. Incorporating such devices into 3DCP structures is relatively simple, and might be useful for monitoring unique bio-inspired complex structures over the long term to ensure their structural integrity.

The use of cellular designs and even topology optimized designs may deliver solutions that are much more porous than traditional designs, this brings with it some inherent multifunctionality such that airflow and thermal insulation is associated with the open porous structure. This function can be incorporated into designs for specific airflow into and around buildings, optimizing the structure for the surroundings and allowing "breathing" buildings. To some extent, the thermal insulation ability of the termite mound has been an inspiration for such building designs in the past [93]. The open porous nature may also have a direct impact on the buildability, allowing the printed concrete to cure faster, due to the open-air flow and large surface area of the porous structures. The incorporation of a "living wall" concept allows plant growth as an optional function of the exterior walls of buildings as developed in [94].

Another multifunctional potential of 3DCP for the future is 4D printing which has been studied so far only for shape memory materials such as some polymers. In 4D printing, an additional dimension is added to the printed object, which is related to the time – for example, to print the object in one shape and apply a thermal or another stimulus to induce a shape change to a different pre-programmed shape [95,96]. Due to the intrinsic hardness behavior of concrete, it is quite impossible to apply 4D printing technology in the same way directly, since its shape change behavior is very limited. However, in combination with other materials or technology, the function of concrete elements can be extended to a new paradigm similar to the benefits found in 4D printing, by "programming" and planning for new functions which are implemented after printing.

An example could be a smart ventilation system in a building which is defined by its ability to be responsive to the users, outdoor temperature, air movement, etc., and regulates ventilation rates in time or by location. Furthermore, smart ventilation systems can provide information to building residents on operating energy consumption and indoor air quality. Being responsive to energy consumption means, providing flexibility to the electricity demand by the residents in the building. Manufacturing of smart ventilation may often require advanced technologies and materials to achieve the maximum benefits. One option could be a composite material, which is a combination of 3DCP materials and shape alloy materials. In this case, a hollow/lattice shape 3D-printed structure can be made together with the amenities that can provide on-demand ventilation facilities inside the room.

Natural materials also demonstrate their multifunctional capabilities and excellent mechanical performance through incorporating multiple material systems into their hierarchical composite architecture such as in nacre, spider silk and collagen. In these biological paradigms, the combination of soft and hard phases in laminar, helicoidal or tubular architectures give them unique performance against external loadings. Recent efforts have been devoted to replicate such multimaterial strategy through biomimicking or structural optimization. Tran et al. [97] demonstrated the use of a dual nozzle FDM printer to replicate multi-material composites at the structural scale of nacreous composites. While the FDM system is limited to only two materials, the recent material jetting technique could provide a much wider range of multi-material printing capability as demonstrated in Tee et al. [98]. There are potential opportunities to employ similar techniques for different material printing systems such as metal and concrete in the near future. Multimaterial optimization is another approach to optimize the performance of a structure given a multiple choice of materials to select from. The designed material then varies locally in mechanical properties such as elastic modulus and density, which will be incorporated in the numerical design framework with the constraints in the volume or mass. Recent work by Nguyen et al. [99] demonstrated this technique and its application to additive manufacturing.

9. Bio-inspired and sustainable materials for 3DCP

Sustainable materials in 3DCP and incorporation of biological or natural materials into 3DCP inherently follow biomimetic principles, and therefore are discussed here briefly. Cement production accounts for almost 8% of the global anthropogenic CO_2 emissions. In 3DCP, the concrete can be precisely placed as per the need, and this can potentially reduce material usage and consequently reduce the construction waste and carbon footprint. Three-dimensional printing of sustainable construction materials can also save time, cost, energy and reduce pollution without compromising the required mechanical properties [100]. However, the material formulation for 3DCP application is a challenging task, and it also depends on the printing mechanism, as shown in Fig. 10. Most 3DCP is extrusion-based, as discussed so far in this paper. However, the concept of digital concrete [101] is wider and incorporates many other processes which may have the potential for bio-inspired and biomimetic structures. Bio-inspired and sustainable materials are discussed in the context of different 3DCP methods below.

9.1. Extrusion based 3DCP process

Concrete printing and contour crafting [102] are both extrusion-based 3D printing processes where fresh concrete is laid layer-by-layer following the digital model. The mix design of fresh concrete must be thixotropic in nature to allow smooth extrusion and proper shape stability of the filament [103–106]. In typical extrusion-based 3DCP, the material travels from hopper to extruder via a concrete pump, and then the printer deposits the material by controlling

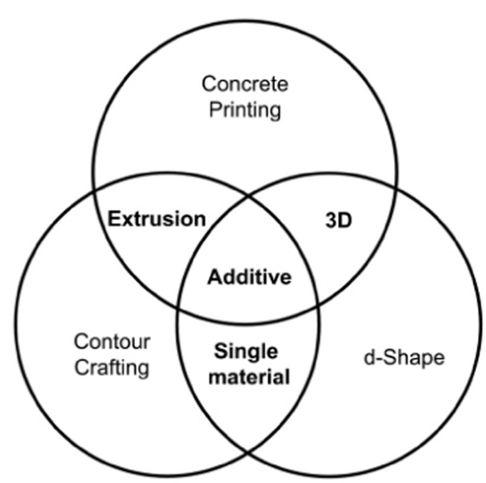

Fig. 10. 3D printing process classification in construction [101].

Fig. 11. (a) extrudability and (b) buildability in 3D concrete printing process [116].

the movement of the extruder. It is clear from this process flow that during pumping, the material needs to have a low viscosity. At the same time, after deposition, it must possess high yield stress for stability and buildability of the extruded layers. These contradicting properties can be fulfilled by designing thixotropic material and controlling the structural built up rate. The material development process in 3DCP needs to satisfy the three main criteria: (1) extrudability, (2) shape stability and (3) buildability (Fig. 11) [12].

Literature reveals that ordinary Portland cement (OPC) has been the most frequently used material to develop 3D-printable concrete as OPC exhibits excellent thixotropic properties when mixed with water [107]. The origin of thixotropy is related to colloidal flocculation along with ongoing hydrate nucleation [108]. However, recently there is an increasing interest in studying the properties of sustainable printable concrete in which OPC is partially replaced by supplementary cementitious material (SCM), including fly ash (FA), silica fume (SF) and ground blast furnace slag, etc. Replacing OPC with SCM, particularly FA, contributes to lowering the CO_2 emission, which is an issue since the cement production leads to massive CO_2 generation [109–113].

Panda et al. [114] have investigated the rheological property of cementitious materials with different levels of FA and SF. The results showed a decrease in yield stress with an increase in FA replacement which is attributed to the ball-bearing effect of spherical FA particles. They also observed good thixotropic behavior of printable materials with SF addition. SF improved the structural build-up rate and a similar observation has been reported in [115]. As a sustainable building material, geopolymers are also formulated for 3DCP application. Panda et al. [116] designed a fly-ash based geopolymer composite with nanoclay for improving the buildability properties. It was concluded that the activator viscosity plays an important role in affecting the final viscosity. The geopolymer reaction is completely different from PC hydration reaction and therefore, proper control of raw material quantity that indirectly controls the reaction rate is need for 3DCP [117]. Since the geopolymer material is produced from only industry by-products, it is difficult to obtain constant material properties for the above-mentioned applications. To avoid the problems related to liquid silicate, Nematollahi et al. [118] designed one-part geopolymer using powder silicates. Panda et al. [119] also used powder silicate to produce 3D-printable geopolymer and found better printability properties compared to liquid silicates. Instead of designing 3D concrete using fly ash and OPC, researchers have also used limestone calcined clay cement (LC^3), earth-based concrete, sulphoaluminate cement (SAC), Magnesium potassium phosphate and calcium sulphoaluminate cement (CSAC) aiming for the sustainable built environment [120–124]. These materials are of low-CO_2 cement for 3D printing, which means their manufacturing process releases less CO_2 compared with the production of OPC.

Similar to binder, river sand aggregate has also been replaced by industry waste products such as recycled glass, crumped rubber, copper tailing etc. Despite sand being a natural resource, it is becoming scarcer, and some countries lack this natural material for construction projects. Utilizing waste or recyclable materials as raw materials in 3DCP can further improve sustainability in our built environment. However, there are still limitations to its use. It is concluded from a study by Ting et al. [125] that partial replacement of sand with recycled glass decreased the concrete viscosity, which facilitates smooth extrusion of printable concrete compared to the control sample. Ma et al. [126] used copper tailing for 3DCP application and based on the measurements, the optimal mixture was determined as substituting natural sand with 30% mass ratio of mining tailings, which enables structures to achieve an acceptable buildability and a relatively high mechanical strength.

Three-dimensionally printed concrete often lacks ductility, and therefore researchers have added different types of fibers to improve tensile properties of the specimen. Figueiredo et al. [127] investigated

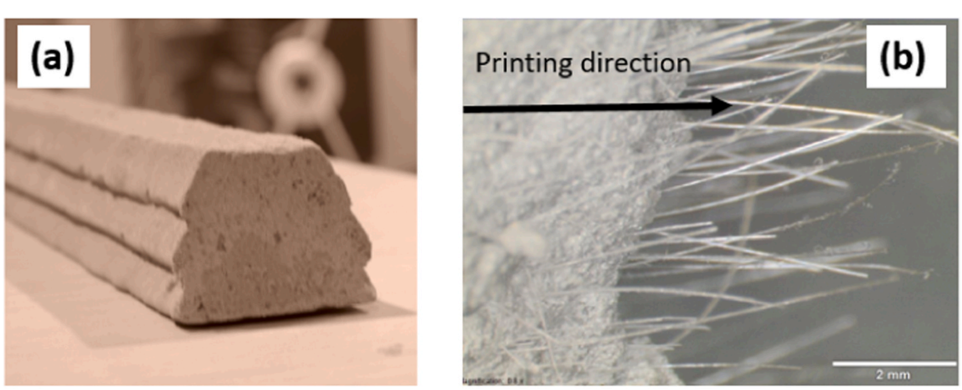

Fig. 12. Fracture image of (a) 3D-printed sample and (b) aligned fiber in the printing direction.

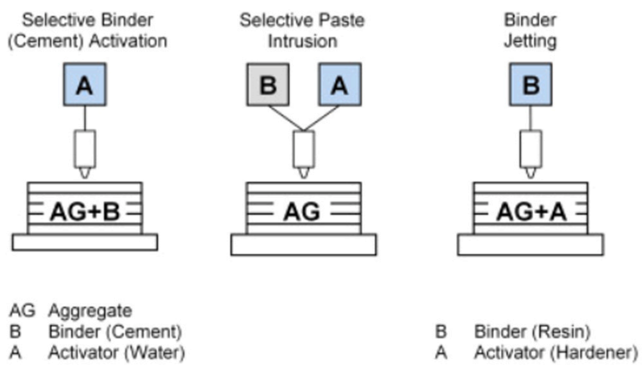

Fig. 13. Schematic representations of different selective binding particle-bed 3D printing [132].

the effects of PVA fibers on the shear yield stress and bulk yield stress of the cementitious materials. In most cases, the increased fiber content had a positive effect on both bulk and shear yield stress. Zhu et al. [128] investigated the effect of PE fibers on the mechanical properties of printed specimens with about 60% cement replaced by FA. They found the flexural strength was improved as PE fibers increased to 2%. The origin of this improvement lies in the strong fiber-matrix bond and alignment of fibers along the printing direction, as shown in Fig. 12. Similar studies [100,129] have been conducted by several researchers to improve the properties of the 3D-printed concrete composite, however, the addition of natural fiber remains as a future research scope for 3DCP application.

9.2. Powder-based 3DCP process

The powder-based approach is one of the methods for selective binding particle-bed 3D printing, alongside selective cement activation and selective paste intrusion [101]. The powder-based method of 3DCP has been said to have the potential to produce small-scale building components, permanent formworks, and precast elements for site erection [130]. Typically, the method functions by building an element using a scaffold approach [74]. The printer head selectively jets binder liquid, often referred to as "ink", through the nozzle(s) onto the different layers of printable powder at a time, which causes the powder at each layer to bind together. This process is continued until the element is wholly formed and then removed after a specified drying time while loose powders are blown away with an air blower. The method guarantees the manufacture of precast sections away from the site environment. The schematic diagram in Fig. 13 shows the three methods of selective binding particle-bed 3D printing. Fig. 14 shows a more detailed approach to the powder-based method of the 3DCP. This approach can create complex geometries of structures with more accuracy compared to the extrusion-based approach [130,131].

9.3. D-Shape

The D-Shape technology which is a powder-based method, operates by the deposition of a binder selectively unto the powder or a large-scale sand-bed [130,132], and it is said to resemble the Z-Corp 3D printing approach. The binding materials used for D-Shape technology is sand and magnesium oxychloride cement [130]. Enrico Dini developed the technology, and it is said to be a fast process in 3DCP not requiring the use of formwork. One of the structures produced using this process is the "Radiolaria" architectural piece measuring 1.6 m shown in Fig. 15.

9.4. Other methods

Another recent development with the powder-based method of 3DCP is the Emerging object, which has been developed in the United States. This method of printing works by activating the dry cement-bed with

Fig. 15. Architectural piece by D-Shape process [132,133].

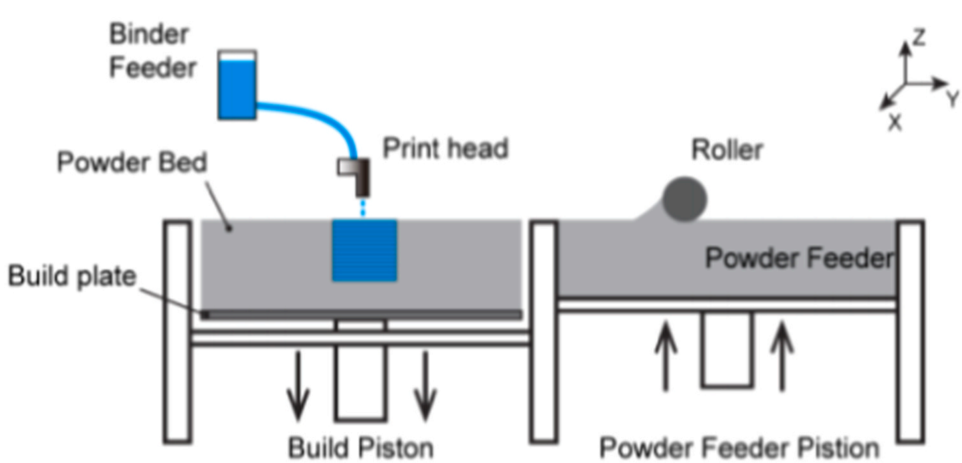

Fig. 14. Schematic representation of powder-based method of 3DCP [130].

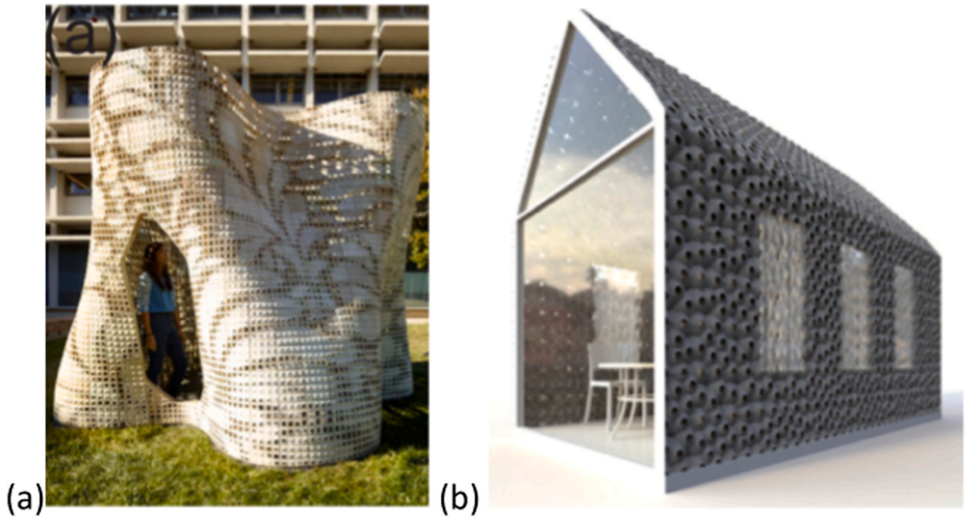

Fig. 16. Structures manufactured by Emerging Objects (a) Bloom (b) Shed [132].

water and polymer [134]. Fig. 16 shows two structures, Bloom (2.74 m tall; 3.6 × 3.6 m footprint, and 840 customized printed blocks), and Shed (printed from sand measuring 0.3 cubic meter) [132]. The development of powder-based techniques, particularly the D-shape methods holds great potential in the near future for the construction industry as elements can be printed off-site and assembled on-site within a short period and at a lower cost and with higher complexity compared to the traditional approach.

10. Future perspectives

Three-dimensional concrete printing is demonstrating industrial relevance in large scale construction and holds huge potential due to its unique capabilities to manufacture complex designs, on-demand, on-site or off-site, customized and especially automated (and therefore relatively fast). Despite the current limitations due to materials and process issues, progress is rapidly being made in this research area so that we can make full use of the available complexity of this additive manufacturing technology. The principles of biomimicry and bio-inspiration may be key to this as they provide the context in which new types of structures can be designed, including optimized material use, tailored mechanical and other properties, the possibility for multiple functionalities and overall higher sustainability. The key to success here lies in understanding the foundations of biomimetic/bio-inspired design and the limits of 3DCP technology. This perspective paper has outlined the fundamental idea of bio-inspired 3D concrete printing in the hope that future work in this direction leads to disruptive new construction capabilities.

Declaration of Competing Interest

One of the authors of this article is part of the editorial board of the journal. To avoid potential conflicts of interest, the responsibility for the editorial and peer-review process of this article lies with the other editors of the journal. Furthermore, the authors of this article were removed from the peer review process and had no access to confidential information related to the editorial process of this article.

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