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Review

Techniques and strategies in extrusion based 3D concrete printing of complex components to prevent premature failure

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3D concrete printing with coarse aggregates

A B S T R A C T

Extrusion based 3D Concrete Printing (E-3DCP) is a rapidly growing method of construction due to its ability to manufacture bespoke architectural and structural elements without incurring the additional time and costs typically associated with the manufacturing of the formwork of these components. However, Complex geometries such as overhangs, bridges, and cantilevers pose significant challenges to E-3DCP, increasing the risk of premature failure during 3D printing and complicating the integration of longitudinal reinforcement. In response to these challenges, researchers have developed various techniques and strategies to mitigate these complexities and failures. This paper provides a comprehensive review of these methods, evaluating their advantages and disadvantages, and identifying research gaps in the current literature.

1. Overview and current challenges in extrusion-based 3D concrete printing of complex geometries

Extrusion-based 3D Concrete Printing (E-3DCP) is a method within the broader category of 3D Concrete Printing (3DCP) [1]. This fabrication method involves a layer-by-layer deposition process where a cement based mortar [2–4], is pumped and precisely deposited by a 3D printing nozzle mounted on a gantry system or a robotic arm [4,5]. E-3DCP promises multiple benefits in the construction field; of most relevance to this paper is the technology's ability to manufacture bespoke architectural and structural elements without incurring the additional time and costs typically associated with the manufacturing of the formwork of bespoke components [2,6,7]. Despite these advantages, multiple challenges still need to be addressed when manufacturing complex components [2,8–11]. Complexity in the context of the paper refers to components with geometries that incorporate the one or a combination of the following features: overhangs, cantilevers, or bridges (Fig. 1).

The inherent evolutionary nature of concrete, combined with the use of a continuous feed pump in E-3DCP, necessitates the coexistence of several conflicting characteristics simultaneously [8,12]. The concrete must be sufficiently fluid to allow smooth pumping and extrusion without clogging the 3D printing system (pump, hoses and 3D printing head / extruder) [12]. However, once the concrete filament is extruded, it must rapidly develop strength and stiffness to preserve its shape and ensure effective buildability which requires the setting of the freshly deposited filament [13]. Yet, this setting cannot be immediate, as the extruded concrete must retain adequate workability to ensure proper adhesion between layers and prevent the formation of cold joints [4,9]. Meeting these conditions requires an intricate balance between various material and fabrication parameters such as nozzle 3D printing speed, layer height, slicing orientation, room ambient temperature, and the acceleration of concrete's setting time [2,14–16]. An imbalance in these parameters causes errors that misalign the center of mass of the 3D-printed filaments, preventing the layers from developing sufficient static yield strength to withstand the loads exerted on them during the 3D printing process by the newly 3D printed filaments and the nozzle. This leads to one or combination of the two most common failure mechanisms in E-3DCP: elastic buckling or plastic yielding of the component being printed [5,8,17,18].

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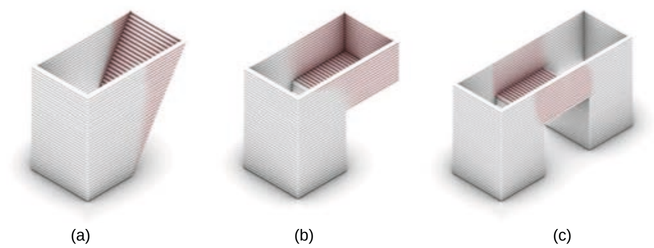

Fig. 1. Complex geometries features: (a) Overhangs, (b) Cantilevers, (c) Bridges.

Complex geometries exacerbate the aforementioned paradoxical properties and make it more difficult to achieve successful 3D prints as they introduce additional challenges in maintaining structural stability and precision during the 3D printing process; this is a result of the varying shapes and angles that exist in complex geometries which can put uneven stresses on the freshly 3D printed concrete [8]. Such geometries are not just essential elements in architectural features like walls with windows and doors but are also frequently encountered in optimized components. Given their prevalence in structural and architectural components, addressing the challenges associated with the 3D printing of complex geometries is of crucial importance [10,14], which drove researchers and practitioners in various fields to innovate new methods that can prevent the premature failure of complex components during the 3D printing process. This paper presents a comprehensive review of the techniques and strategies employed in E-3DCP for fabricating components with complex geometries.

2. Methods and approaches to prevent premature failure and enable the fabrication of complex geometries

Strategies for addressing the challenges of complex geometries in E-3DCP fall into three main categories: a) rationalizing design and slicing strategies for compliance with E-3DCP constraints, b) utilizing support to mitigate the geometric complexity, and c) stay in place sequential casting to scaffold the E-3DCP parts (Fig. 2). This section discusses these categories in-depth and provides insights into how each approach contributes to overcoming the challenges posed by complex geometries in E-3DCP.

2.1. *Rationalizing geometry of the 3D printed parts while maintaining a horizontal planar slicing*

Rationalizing the geometry of 3D printed parts involve designing or modifying the part's design to align with the geometric constraints of E-3DCP while maintaining a horizontal planar slicing of the 3D printed part; this approach is primarily utilized in 3D printing components with overhangs and bridges. To identify these constraints, Brun et al. [10] conducted an experimental study to determine the impact of various concrete mixtures on the buildability of overhangs. A truncated pyramid with each side at varying slopes of 7°, 10.5°, 14°, and 17.5° was used as the benchmark part of the study (Fig. 3a). The testing parameters were set at a 3D printing speed of 40 mm/s, 8 mm layer height and target layer width of 20 mm. The mixture that yielded the best results was capable of 3D printing seven layers while achieving a maximum overhang of 17.5° (Fig. 3b). This mixture had a cement to fly ash ratio of 70 to 30 %, including 1 % superplasticizer and 0.5 % hardening accelerator. This concrete mixture's consistency was between 160 and 175 cm slump, with a workable life of 30 min.

In their research, Brun et al. [10] utilized a single pump for both the concrete and the accelerator. To avoid blockages in the pumping system, the concrete mixture was designed to retain sufficient workability, necessitating the use of a restricted quantity of hardening accelerator. In addition to the conservative addition of the accelerator, the experiments were carried out on a small-scale part, which potentially did not provide the freshly 3D printed concrete enough time to gain the strength required to support steeper overhangs. Therefore, either accelerating the concrete's setting time or allowing longer setting periods could potentially enable the construction of steeper overhangs. Muthumanickam et al. [19] provided evidence that it was possible to achieve overhangs with angles up to 25°. In addition to academic researchers, providers of heated nozzle concrete tool heads such as Build Additive [20] (Fig. 4a) and those offering 2K systems like VERTICO [21] (Fig. 4b), Baumit [22] (Fig. 4c), and XtreeE [23] (Fig. 4d), have also demonstrated the capability of their systems to construct overhangs of comparable angles. Achieving steeper overhangs is advantageous not only because it can help remove the need for supports for complex geometries but also because they can be utilized to substitute other design features that require supports, such as bridging geometries as shown by Alabbasi et al. [24] (Fig. 4e), Duarte et al. [25] (Fig. 4f), and Tay et al. [14] (Fig. 4g).

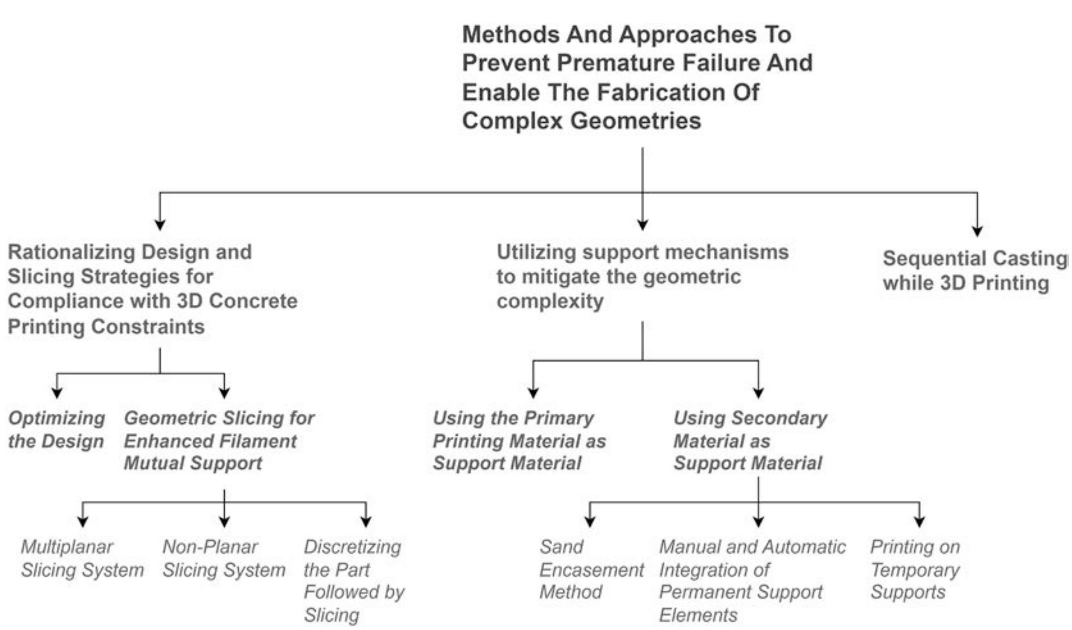

Fig. 2. Categorization of the methods and approaches used to prevent premature failure and enable the fabrication of complex geometries.

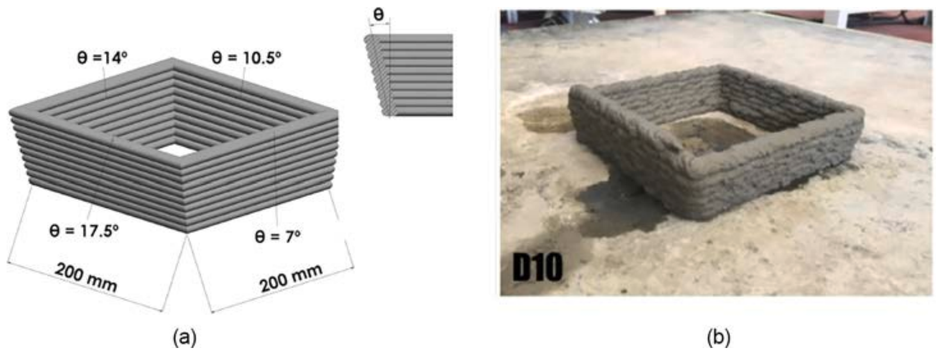

Fig. 3. Drawings of the specimens 3D printed: a) 3D model of the part used for benchmarking the experiments, b) 3D printing of overhangs experiments [10].

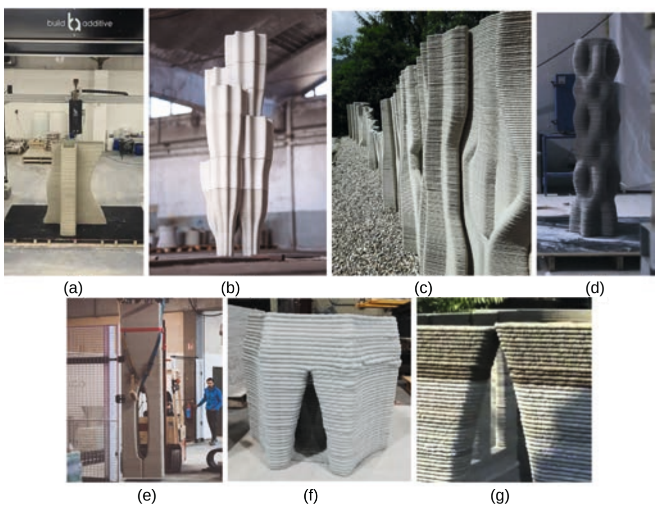

Fig. 4. Fabricated examples of E-3DCP parts featuring overhangs: a) Part 3D printed using Build Additive [20] heating nozzle, b) Part 3D printed using Vertico [21,26] 2K system, c) Part 3D printed using Baumit's Bauminator [22,27] 2K system, d) Part 3D printed using X-treeE [23,28] 2K system, e) An example of the work presented by Alabbasi et al. [24] using overhangs as a method to create openings, f) An example of the work presented by Duarte et al. [25] using overhangs as a method to create openings, g) An example of the work presented by Tay et al. [14] using overhangs as a method to create openings.

2.2. *Geometric slicing for enhanced filament mutual support*

Horizontal planar slicing (Fig. 5a), a process where with an extrusion-based end-effector directly prints concrete layer-by-layer along a planar print-path parallel to the ground [4,29,30], simplifies the fabrication process by minimizing the number of fabrication related parameters to be managed. However, rationalizing a part's geometry to fit this planar slicing method can be suboptimal in several scenarios. First, it may complicate the 3D printing process, necessitating the use of extensive supports. Second, horizontal planar slicing can significantly alter the features of some parts, which might lead to the final 3D printed part deviating from the original design intent both in form and function. Third, this approach can exacerbate the anisotropic properties of extrusion-based concrete 3D printed parts [31,32], which might negatively impact their structural integrity and overall performance. Shifting the focus of slicing towards enhancing the filament mutual support has the potential to streamline the 3D printing process and significantly improve the structural coherence of the 3D printed part. Aside from horizontal planar slicing, other slicing systems utilized for filament mutual support in E-3DCP can be divided into the following three categories: a) multiplanar slicing (Fig. 5b), b) non-planar slicing (Fig. 5c), and c) discretizing the part followed by slicing (Fig. 5d).

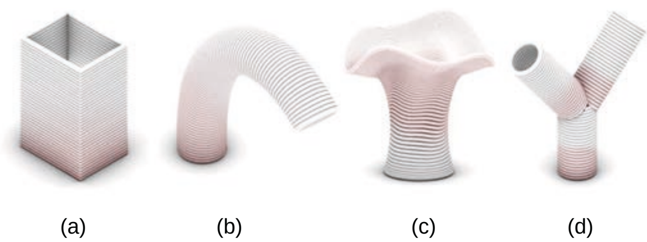

Fig. 5. Slicing systems: a) Horizontal planar slicing, b) Multiplanar slicing, c) Non-Planar slicing, d) Discretizing the part followed by slicing.

2.2.1. *Multiplanar slicing system to create complex parts*

The multiplanar slicing system involves slicing the part to be 3D printed to align with its geometrical flow such that all slices at each layer or increment are flat on the same plane. This technique allows for a more natural and coherent representation of the part's contours and shapes in the 3D printing process; in addition, the slicing layers can be utilized to mimic the behavior of self-supporting structures conventionally constructed with masonry-like vaults. The framework for this approach was first proposed by Khoshnevis [33] (Fig. 6a) as a method for supportless 3D printing using contour crafting laying the foundation for the work presented by Carneau et al. [34] (Fig. 6b), where they successfully fabricated a Nubian Vault relying on the multiplanar slicing technique. In this project, to ensure a continuous toolpath and avoid extrusion complications associated with starting and stopping the concrete extrusion, the vault is sliced such that the first layer is perfectly horizontal, gradually increasing to a 40° angle. This section of the 3D printed element is referred to by the authors as the transitional part of the 3D print. Once the 40° angle is achieved, subsequent layers are 3D printed at a consistent angle and constitute the cylindrical part of the structure. For these experiments, the 3D printing speed for the cylindrical part was set at 200 mm/s to ensure a constant interlayer time of 10 s, and a 2K system was utilized as the concrete extrusion system.

Carneau et al. [34] determined that the 3D printing process can achieve angles as steep as 60°, provided that the 3D printing end effector has sufficient accessibility to the 3D printed part and is not in collision with the 3D printing bed. In parallel, the Digital Architecture Research and Technologies (DART) team at the University of Michigan successfully 3D printed overhangs reaching angles up to 30° relative to the *Z*-axis [35] (Fig. 6c). The concrete setting time in that case was accelerated by increasing the ambient temperature and significantly reducing the 3D print speed to 5 mm/s.

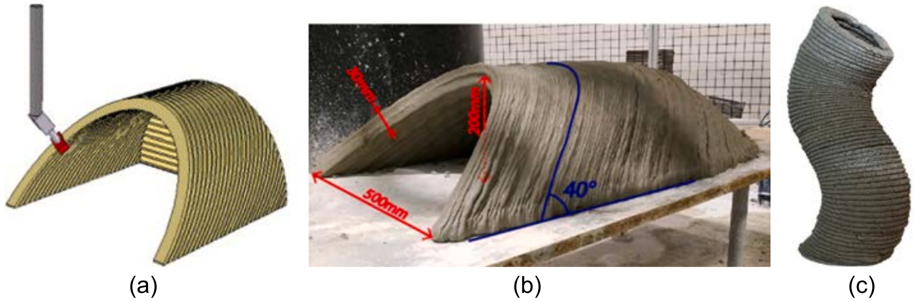

Fig. 6. Multiplanar slicing system examples: a) Framework proposed by Khoshnevis [33] for supportless 3D printing of vaults, b) Results achieved by Carneau et al. [34] for printing a Nubian vault, c) Results achieved by the DART team [35] for 3D printing overhangs reaching up to 30° relative to the Z-axis.

2.2.2. Non-planar slicing system to create complex parts

Although multiplanar slicing is beneficial for aligning the 3D print layers with the geometry of the 3D printed part, ensuring that all curves on each slice level are on the same plane can restrict design flexibility. In situations requiring greater design freedom, non-planar slicing systems become advantageous. These systems enable the creation of more complex parts by allowing for varied layer orientations and configurations that are not confined to a single plane, which is not only advantageous from a design flexibility standpoint but also contributes to potentially stronger parts. The reason lies in the ability of non-planar layers to bond in many directions, reducing the anisotropic behavior of the 3D printed part and enhancing the overall structural integrity.

Bhooshan et al. [36] constructed a 16-m-long unreinforced, bifurcating, compression-only footbridge by adopting non-planar 3D printing techniques, dividing the structure into 53 blocks produced via E-3DCP. Each block was non-planarly sliced (Fig. 7a) to ensure layers were orthogonal to the compressive forces, allowing effective force distribution. Similarly, Carneau et al. [34] fabricated a self-supporting pointed arch (Fig. 7b), addressing the challenge of maintaining the stability of overhangs during 3D printing by adopting a non-planar slicing strategy for structural integrity. Lin et al. [37] further demonstrated the capabilities of non-planar slicing in creating complex structures by fabricating a topology-optimized wall (Fig. 7c).

2.2.3. Discretizing the part followed by slicing to create complex building parts

In non-planar and multiplanar slicing methods where the 3D print path planes vary from one layer to the next, variable material deposition may be needed due to the differing layer heights [35,37]. One method utilized in E-3DCP to avoid these complications is discretizing the part followed by slicing each discretized part. This method aims to break down the 3D printed part into less complex parts that can be individually tailored to the part's geometry, which allows each section of the geometry to be 3D printed with optimal layer orientation. The utility of this method was showcased by Motamedi et al. [38], who drew on the supportless techniques of Persian vault construction, in particular the Filpoosh vaulting method, to 3D print quad-based domes. Their approach used an algorithm to divide a dome into a series of arches,

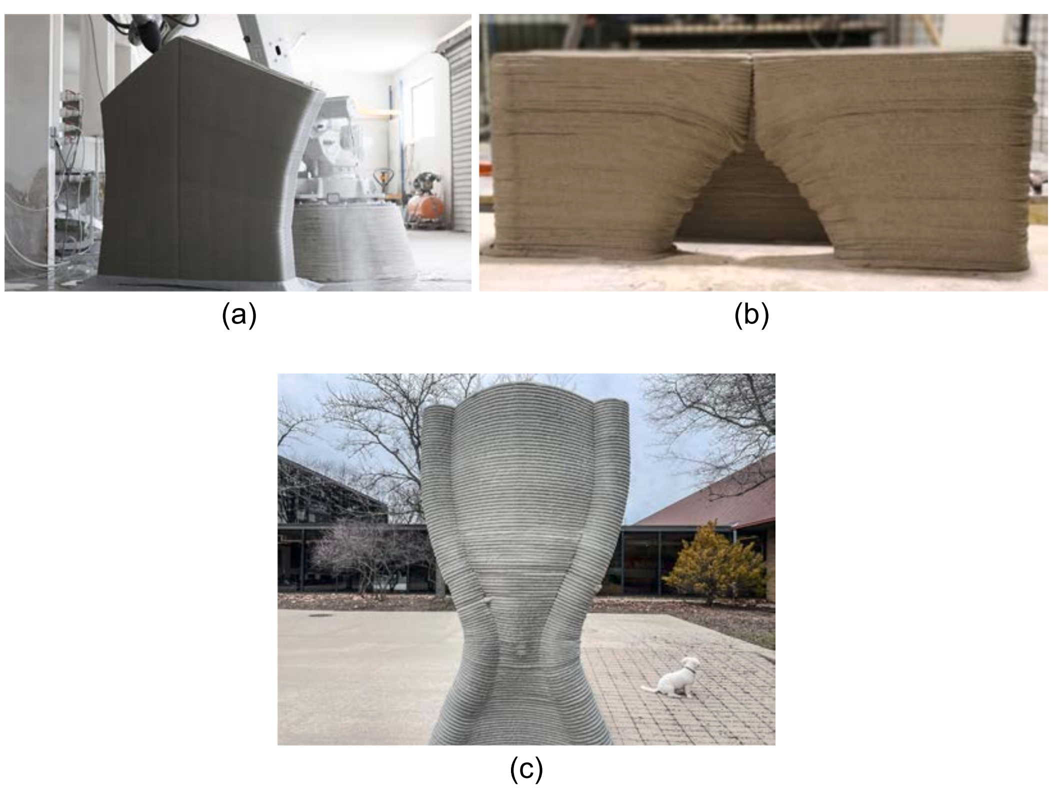

Fig. 7. Non-Planar slicing system examples: a) One of the 53 blocks presented by Bhooshan et al. [36], b) Self-supporting pointed arch presented by Carneau et al. [34], c) Topology optimized wall presented by Lin et al. [37].

Fig. 8. Segmented slicing system examples: a) Segmented arch for the E-3DCP of a dome presented by Motamedi et al. [38], b) Branched structure shown by Bhooshan et al. [39].

which were then 3D printed as segments to create the complete structure (Fig. 8a). Similarly, Bhooshan et al. [39] applied this method to branch-like structures. They interpreted the geometry as a skeletal graph, breaking it into manageable parts. Each segment was then 3D printed in sequence, which was crucial for the structural integrity and overall success of the 3D printing process (Fig. 8b).

2.3. Using the primary 3D printing material as support material

While optimizing the design and slicing strategy of the 3D printed part can allow the 3D printing of overhanging complex geometries, still when encountered with cantilevering geometries or when freshly 3D printed layers are not allowed enough setting time, these strategies fall short. To overcome these challenges, researchers and practitioners have resorted to support mechanisms to mitigate the geometric complexity and ensure the structural stability of the 3D print. Support mechanisms in E-3DCP can be broadly classified by the type of material used. The first category comprises supports made from the primary 3D printing material, i.e., concrete. The second and more commonly employed category involves supports made from a secondary material distinct from concrete.

Using primary material as support material is not widely adopted by researchers and practitioners; this is often due to the higher costs and potential waste associated with using concrete for supports. However, there are notable advantages to this approach. Firstly, it streamlines the logistics of material handling, potentially speeding up the 3D printing process and reducing the risks involved with manual intervention for support placement during active machine operation. Secondly, employing the primary material for supports ensures consistent shrinkage across the 3D printed part.

Within the scope of the discussed paper, employing the primary material as support implies that the section designated as support is not a load-bearing part of the structure; this non-structural section may either be left in place or removed through post-processing. Tay et al. [40] in their paper presented a functionally graded truss (Fig. 9a); the authors manipulated the travel speed of the 3D printing system, reducing it at the structural part to allow for higher flow rate while the travel speed was increased at the support parts to allow for less material deposition, the support parts were left in place but by depositing less material at non-structural part the 3D printed part can be of lighter weight, the results presented by the authors achieved approximately 50 % improvement in weight to body ratio. In another paper, Tay et al. [14] presented a similar approach to constructing removable supporting material. The presented case study was an opening in a wall; the authors manipulated the travel speed to control the material deposition, strategically weakening the filament in support areas. This created a support wall that could be easily removed during post-processing (Fig. 9b). Gaudillière et al. [41] employed a different method for a truss-like pillar, where they ensured printability by connecting voids with a temporary surface. This surface was subsequently removed in post-processing

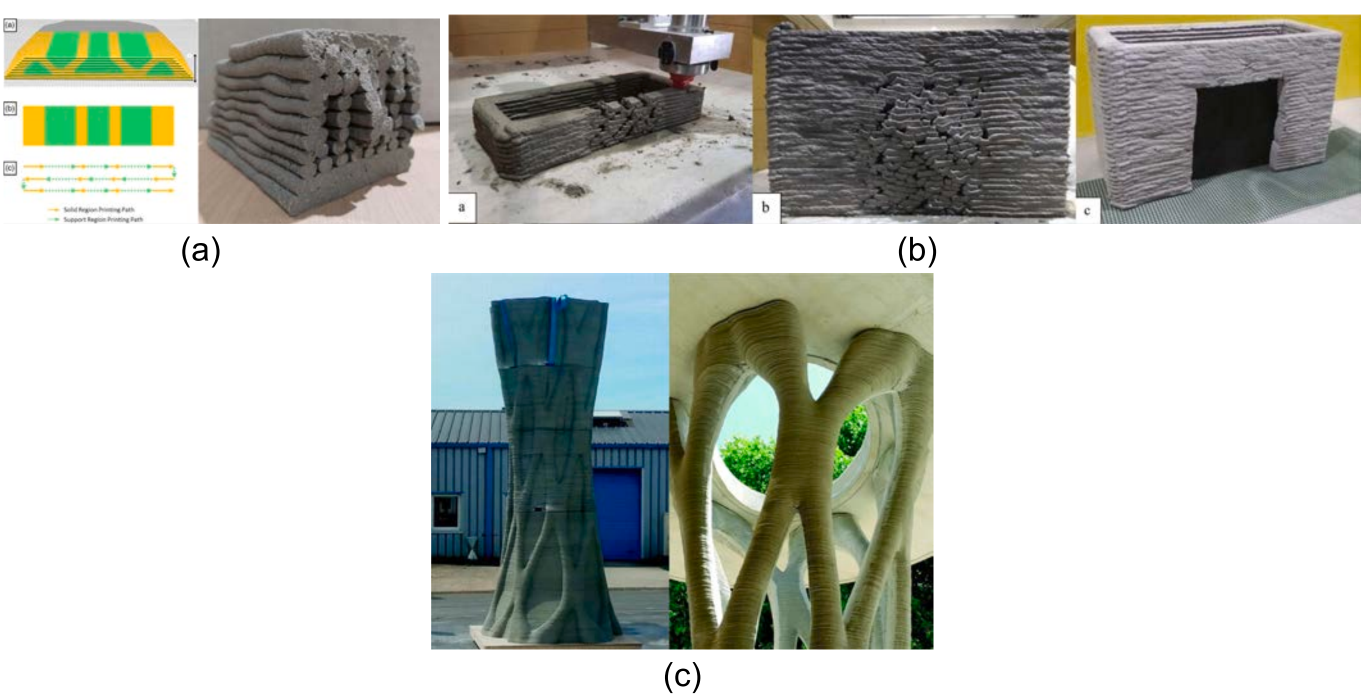

Fig. 9. Primary 3D Printing Material as Support material examples: a) Functionally graded truss presented by Tay et al. [40], b) Wall opening case study presented by Tay et al. [14], c) Truss-like pillar presented by Gaudillière et al. [41].

(Fig. 9c).

2.4. Using the secondary material as support material

The widespread adoption of secondary materials for support in E-3DCP is a result of the several advantages this method presents over using concrete as support material. Firstly, secondary materials can be more cost-effective and time-efficient. Additionally, they provide greater flexibility in material selection, allowing researchers to determine whether the support will be a load-bearing part of the final structure and whether it is intended to be a temporary or permanent element of the construction. This flexibility enhances the versatility and applicability of E-3DCP in various construction scenarios. Using Secondary material as support material can be classified into the following three categories: a) Sand encasement method, b) Manual and automatic integration of permanent supportive elements, and c) 3D printing on temporary supports.

2.4.1. Sand encasement method

The sand encasement method is a useful support method for 3D printing slurry non-Newtonian fluids like concrete. In this method, the 3D printed part is surrounded by sand, which acts as a physical support for the part during the 3D printing process. Pouring the sand around and inside the 3D printed part needs to be done in a sequential manner as the part is being 3D printed, typically through a manual process, which can be hazardous in some cases or result in interrupting the 3D printing process. After completing the 3DCP process, sand is removed from the 3D printed part, which presents additional challenges. The manual sand removal process is time-consuming and labor-intensive, and clearing sand from intricate geometries is difficult due to small, enclosed spaces where sand particles can be trapped, making complete removal challenging. Lastly, larger printed objects require more sand, adding to the complexity. Sand is becoming an increasingly scarce material [42–45] and their multiple negative environmental impacts that sand extraction and disposal have, such as habitat destruction leading to biodiversity loss [42,44,46], water pollution [45,47,48], groundwater depletion [49], and air pollution [50].

Nevertheless, the sand encasement method has multiple advantages as it eliminates the need to design and 3D print dedicated support structures as the sand is poured around the part. Moreover, this method facilitates a smoother post-processing phase, as the sand can be easily removed once the concrete has cured without leaving marks or requiring additional finishing work. And finally, this method also offers the potential for recycling and reusing the sand used for supports which can help mitigating the negative impact of sand extraction and disposal. Multiple researchers have demonstrated the utility of utilizing the sand encasement method, Vantyghem et al. [51] utilized this method for 3D printing a topology-optimized concrete girder (Fig. 10a), and it was similarly applied in the work presented by Ooms et al. [8] (Fig. 10b), Bekkering et al. [52] (Fig. 10c), Ahmed et al. [53] (Fig. 10d) and, Ahmed et al. [54] (Fig. 10e).

2.4.2. Manual and automatic integration of permanent support elements

The integration of permanent supportive elements typically serves to provide structural support for newly 3D printed layers during the 3D printing process and become load-bearing components upon the completion of 3D printing. While this structural application dominates the application of this method, some researchers have used permanent supports as non-structural spacers or as supports for bridging geometries [56] (Fig. 11a). Permanent supports are widely adopted by practitioners in the construction of houses for doors and windows openings this can be seen in the houses constructed by companies like Icon [57] (Fig. 11b), SQ4D [58] (Fig. 11c) and Be More 3D [59] (Fig. 11d). These supports are manually inserted, a process that has prompted Hoffmann et al. [60] to develop an automated alternative. They created a multi-tool end effector that combines a gripper and a 3D printing nozzle. The gripper is

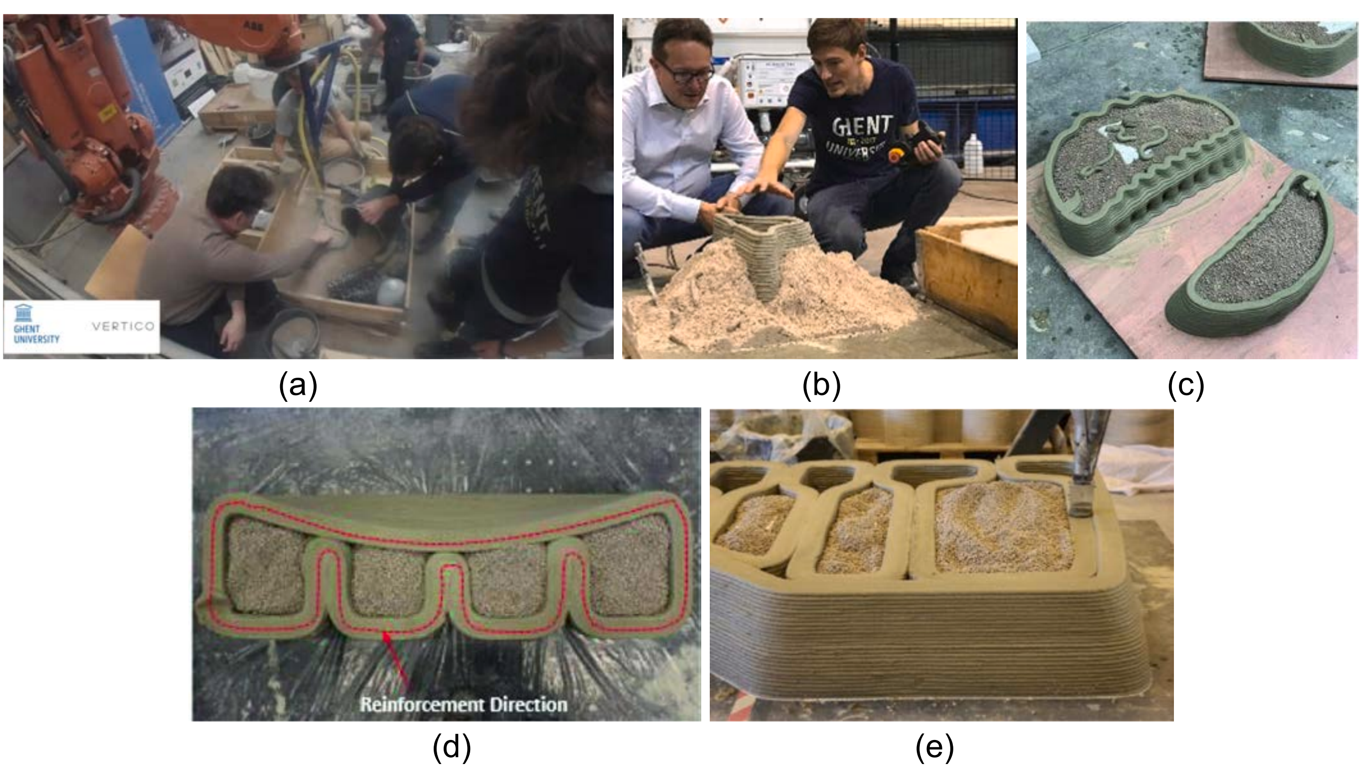

Fig. 10. Examples of the Sand Encasement Method in E-3DCP: a) A team actively applying the sand encasement method around a structure in progress, as demonstrated by Vantyghem et al. [51,55], b) Work presented by Ooms et al. [8] where sand surrounds the base for support, c) The technique utilized by Bekkering et al. [52] where sand is strategically placed within the 3D print's interior voids, d) Ahmed et al. [53] also show sand filling internal cavities to support overhangs, and e) Further application by Ahmed et al. with sand supporting intricate geometric shapes [54].

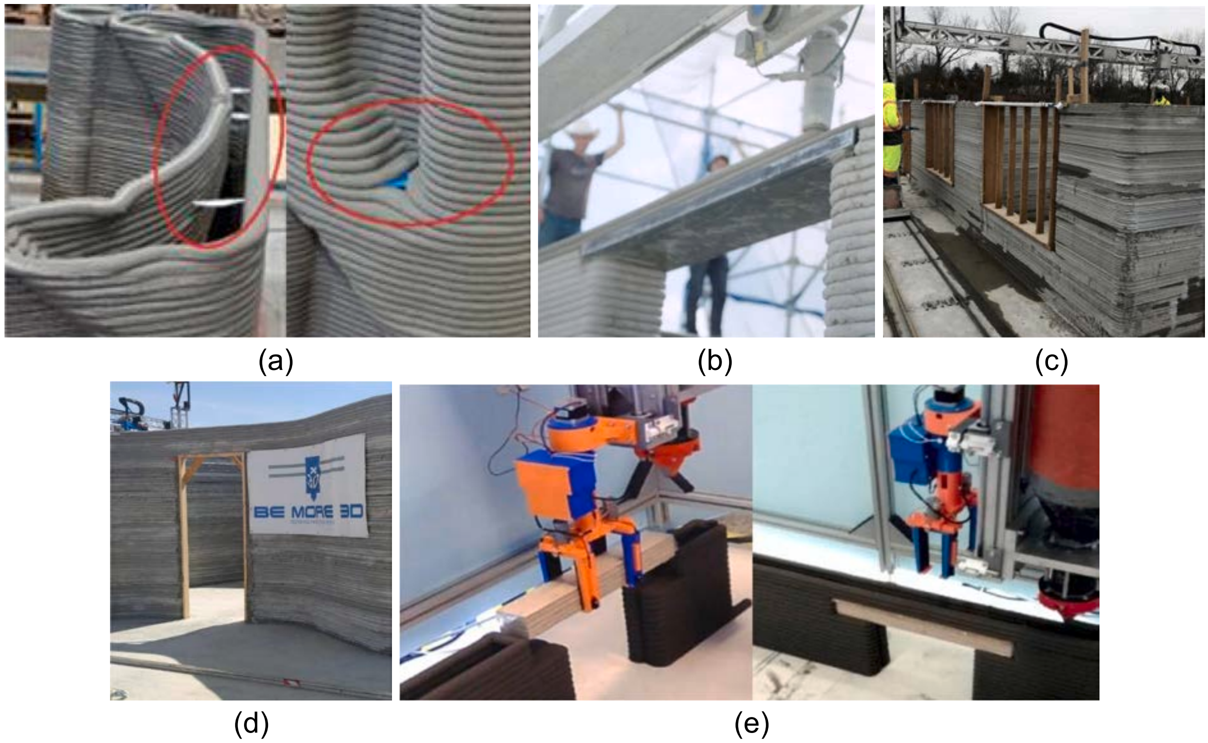

Fig. 11. Examples of manual and automatic integration of permanent support elements: a) Work presented by Ooms et al. [56] showcasing the placement of PLA 3D printed spacers and supports, b) A house constructed by Icon showcasing the 3D printing process over a window lintel [61], c) A window frame and lintel placement in a house built by SQ4D [62], d) A door frame after the completion of the printing process of a house constructed by Be More 3D [63], e) The multi-tool end effector for placing window lintels and printing by Hoffmann et al. [60].

designed to execute pick-and-place tasks, accurately positioning window lintels, while the 3D printing nozzle resumes the 3D print job once the support is in place (Fig. 11e).

2.4.3. 3D printing on temporary supports

The utilization of temporary supports in E-3DCP enables the construction of complex geometries that are not achievable with traditional support methods. These temporary structures provide necessary stability during the 3D printing process and the setting of the concrete; once the concrete achieves sufficient strength, the supports are removed. Temporary supports can be reusable, as shown in the work presented by Xiao et al. [64] where they injected concrete into a non-hardening carrier liquid, ground limestone. Their paper presented the design and fabrication process of a structurally optimized table designed through Vector-based 3D Graphic Statics, resulting in spatial structures that are challenging to 3D print with conventional supporting methods (Fig. 12a). On the other hand, the supports can also be non-reusable as presented by Duballet et al. [65] where they hotwire cut modular pyramids out of EPS foam that, when assembled form the polyhedra for a space truss, each one of the pyramids had grooves to support the concrete filament (Fig. 12b). The EPS blocks were placed sequentially in a manual process. However, the authors envision this process to be a collaborative process between two robots where one robot is responsible for 3D printing, and the other robot is responsible for placing the supports.

2.5. Sequential casting while 3D printing

A prominent application in E-3DCP involves using the 3D printed part as a stay-in-place formwork, which may or may not be structurally active. In this context, concrete is cast into the 3D printed form after completion of the 3D printing process. An alternative approach is to sequentially cast fast setting concrete while 3D printing [35]. This method allows the cast concrete to serve as a bonding agent, uniting the

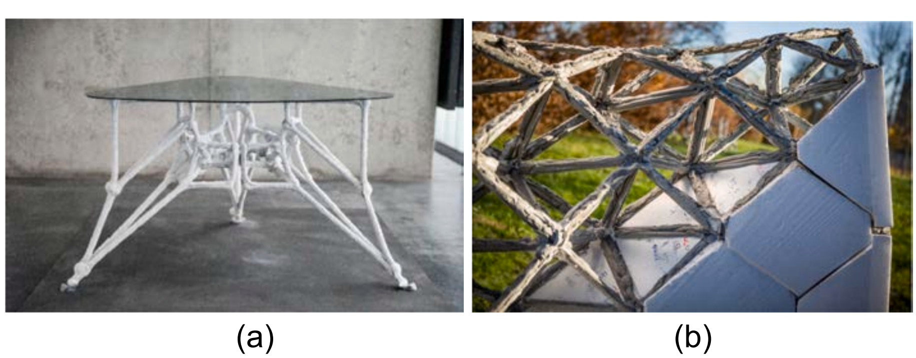

Fig. 12. Examples of 3D printing on temporary supports: a) Case study fabricated table presented by Xiao et al. [64] the legs of the table were optimized using Vector-based 3D Graphic Statics and 3D printed in a limestone-based carrier liquid, b) Space truss 3D printed on EPS foam blocks presented by Duballet et al. [65].

freshly 3D printed layers and facilitating the creation of complex structures. Sequential casting while 3D printing enables manufacturing of highly complex geometries such as sharp cantilever branches without the need of external support. This offers the potential to transform the E-3DCP process into a seamless and waste-free operation, significantly reducing the reliance on external supports.

The process of 3D printing concrete to serve as formwork, followed by casting in both a conventional and sequential approach, presents multiple practical challenges: a) The formwork should be able to withstand the loads during casting. The formwork experiences significant stresses due to hydrostatic pressure from the cast concrete, which cannot support its own weight [66]; b) In the sequential casting while 3D printing process, the fast-setting cast concrete initially transfers moisture to the formwork. As the cast concrete sets, the moisture transfer reverses, with the formwork releasing moisture back into the cast concrete. This process resembles interactions in repair systems and concrete pavements, where the moisture within the fresh mortar is absorbed by the old concrete substrate leading to partial recovery of the initial drying shrinkage but results in irreversible shrinkage [67,68]; c) For 3D printed formwork subsequently used for casting concrete, during hydration, the cast concrete releases heat, leading to a non-uniform temperature rise within the 3D printed formwork [66]. In the case of 3D printed stay-in-place formwork and sequential casting, both the formwork and cast concrete release heat, resulting in a non-uniform temperature rise within

(a)

(b) (c)

Fig. 13. Sequential casting while 3D printing method as demonstrated by Aghaei Meibodi et al. [35]: a) Initial experiments on S-shaped complex geometry with overhangs up to 40 degrees relative to the Z-axis, b) Image taken after casting the concrete into the 3D printed structure, c) The final topology optimized branching wall.

the 3D printed formwork. This differential thermal expansion can lead to thermal curling resulting in cracking, especially in thick elements, due to the inability of the formwork to transfer heat quickly enough. The peak strain occurs during the hydration phase of the cast concrete, leading to residual strains after cooling.

In E-3DCP and sequential casting, synchronizing the 3D printing and casting process is crucial in order to: a) ensure the buildability of the 3D printed part, b) avoid interlayer cold joints, and c) ensures proper bonding between the cast concrete and the 3D printed formwork. Additionally, the height of the casts must be managed to ensure that the hydrostatic pressure of the cast concrete does not exceed the maximum loading capacity of the wet 3D printed formwork. The dimensions of the 3D printed part also play a crucial role, as a wider horizontal cross-sectional area exerts higher hydrostatic pressure on the formwork substrate.

Aghaei Meibodi et al. [35] applied this method to 3D print a topology-optimized branching wall utilizing a fast-setting concrete for sequential casting. The initial experimentation of the method was done on an S-shaped complex geometry that featured overhangs up to 40 degrees relative to the *Z*-axis (Fig. 13a). The setting of the 3D printing concrete formwork was accelerated by raising the ambient temperature of the 3D printing chamber, followed by sequential casting of fast setting concrete. The produced knowledge from these initial experiments guided the production of the branch wall project [35] where the casting of the fast-setting concrete was timed at every 5 mins, and the achieved overhangs were up to 790 mm and 35° angle relative to the Z-axis (Fig. 13b, c).

3. Cementitious-based mortar mix design and its influence on fabricating complex geometry in extrusion based 3D concrete printing

The production of complex geometries in E-3DCP is heavily reliant on the structuration rate (i.e., the rate of increase in static yield stress). The structuration rate should be high enough to ensure sufficient yield strength is developed to support the self-weight of the freshly 3D printed layer as well as the weight of the subsequent layers it carries [69–71]. Unlike 3D printing with materials like metal and plastic, where each layer sets completely before adding the next, this is an undesirable behavior in E-3DCP as it can lead to improper bonding between 3D printed layers leading to the formation of cold joints [72–76]. Therefore, it is critical to have nuanced control over the setting time of concrete.

E-3DCP methods for managing concrete setting, the time at which the concrete mixture starts losing its plasticity [77], can be classified into three main methods. The first method, known as a 1K 3D printing system [78–80], involves pumping the concrete without any modification to its setting time. The second method introduces an accelerator to the slurry to accelerate the setting time and achieve quicker buildability. This is achieved by introducing concrete accelerators to the concrete mix, either by mixing the accelerator and concrete at the tool head using separate pumps, known as a 2K 3D printing system [78–82], or by integrating the accelerator directly into the concrete before it's pumped through a single system [83–85]. The third method involves applying heat to speed up the concrete's hydration reaction; the heat application can be executed directly using a heat gun or a heated nozzle, or by manipulating the ambient temperature of the 3D printing environment [35,37].

Regardless of the E-3DCP system approach to concrete setting, there are certain favorable properties that the base mortar being pumped needs to exhibit: a) minimal slump concrete is desired to avoid deformation in part being 3D printed [86], b) the concrete must be pumpable, pumpability refers to the material's mobility and stability under pressure while maintaining its initial properties including workability, consistency, slump, strength and durability [87], and c) thixotropic behavior is also desired, where high static viscosity material becomes less viscous when agitated and reverts to high viscosity when at rest [88–90]. Current codes and standards for conventional concrete construction do not apply to the mix design of E-3DCP. As a result, there is no standard concrete mix design ratio in the literature, and most studies rely on trial and error [86,91]. However, mix designs with water-to-binder ratios of 0.20-0.40 and binder-to-sand ratios of 0.60-0.70 have produced the best printability [86]. The maximum particle size is typically limited to less than 2 mm due to pumping requirements, which utilize a progressive cavity pump to ensure continuous and smooth material feeding [86].

In most cases, manufacturing complex geometries with E-3DCP necessitates the accelerated setting of the 3D printed concrete by utilizing one of the above-described systems. Despite their advantages, accelerators increase the exothermic hydration reaction and thermal stresses [15,92]. Extensive use of accelerators can result in reduced long-term strength [92,93]. This reduction in long-term strength can be due to several mechanisms: the alteration of hydration products, leading to a less dense and more porous microstructure; the formation of microcracks due to increased internal stresses; poor quality of the cement paste due to rapid hydration; and chloride-induced corrosion in steel reinforcement, if chloride-based accelerators are used [94,95].

This risk is exacerbated by the fact that conventional E-3DCP concrete mix, being a cementitious-based mortar, does not include coarse aggregates. While some research in the literature has explored the potential of introducing coarse aggregates [96–98], the majority of research done in this area has focused on methods of introducing short fibers either at the tool head or directly to the concrete mix at the pumping stage [31,99–102]. This approach opens the possibility for the implementation of engineered cementitious composites which compensates for the lack of coarse aggregates and minimizes the formation of micro cracks and shrinkage [101]. Although the maximum size of coarse aggregates can have adverse effects on the distribution and orientation of fibers in concrete mixes [103–105], some recent studies have explored the fresh and mechanical properties of E-3DCP with a concrete mix that has coarse aggregates ranging from 5 to 20 mm and steel fiber content of 0 %, 1 %, and 2 % [106].

4. Decision making framework for material design and complexity mitigation in the fabrication of complex parts in extrusion based 3D concrete printing

To effectively navigate the challenges in E-3DCP, particularly concerning material design and the fabrication of complex parts, a two-part decision-making framework is proposed by the authors:

4.1. Material design considerations

Acceleration of Concrete Setting: If sequential casting while 3D printing method is not used, the acceleration of concrete setting is almost always required for the success of E-3DCP of complex parts, either through the introduction of accelerators as admixtures or through heating. While accelerating the concrete setting could help prevent the premature failure of the 3D printed part, it also has multiple downsides if the 3D printed part is intended to be load-bearing, not just a lost formwork. It also introduces additional complications to E-3DCP system:

1. Extensive use of accelerators in 2K 3D printing systems can degrade the concrete's long-term durability and mechanical properties [16]. Specific accelerators, such as calcium chloride, may also induce corrosion in steel reinforcements [9].
2. Dynamic mixers in 2K systems, while effective, are inherently complex and require high maintenance. Precise calibration with concrete and accelerator pumps is essential; improper setups can create 'dead zones' where mixing is inadequate [9].
3. Static mixers reduce the complexity associated with dynamic mixers but necessitate that the concrete and accelerators have matching viscosities [68,107]. This is often achieved by mixing the accelerator

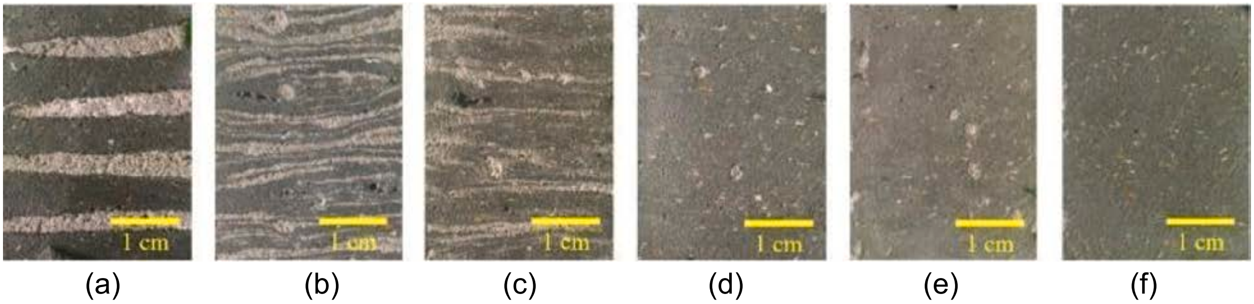

Fig. 14. Example of the effect of the number of mixing elements on the mixture's homogeneity in a static mixer as presented by Tao et al. [9], the dark grey is the 3D printed concrete and the lighter grey is the limestone based carrier liquid: a) 0 elements, b) 6 elements, c) 12 elements, d) 18 elements, e) 24 elements, f) 30 elements.

with a limestone-based carrier liquid. The mixture's homogeneity—and consequently the structural integrity of the 3D print—depends significantly on the number of mixing elements within the mixer [9,12,16,107–110] (Fig. 14). Fewer mixing elements might lead to a heterogeneous mix, while more mixing elements, though improving homogeneity, increase the tool's length and the required pumping pressure, complicating the 3D printing of non-horizontal structures [9].

4. Applying heat as an alternative method for accelerating setting is simpler. Nevertheless, heat application can similarly impair the concrete's later-age structural and mechanical properties [111].

4.2. Fabrication complexity mitigation

1. **Design Rationalization and Advanced Slicing Strategies:** Initially, addressing the geometric complexity of 3D prints should focus on design rationalization and advanced slicing strategies. These techniques minimize the need for additional fabrication complexity by aligning the fabrication parameters of the 3D printed part with the existing E-3DCP system constraints.
2. **Supporting Mechanisms and Sequential Casting:** For structures where geometric rationalization and print path strategies alone are insufficient, employing supporting mechanisms or sequential casting during 3D printing is necessary. These methods are vital for enabling the fabrication of complex geometries and ensuring structural integrity during the critical early stages of setting. Despite their advantages for mitigating the geometric complexity, these methods introduce interruptions to the E-3DCP process which may lead to:
   a. Poor bonding between the newly 3D-printed sections and the freshly cast sections when using the sequential casting while 3D printing method.
   b. Poor interlayer bonding between newly 3D-printed and existing filaments when using either sequential casting while 3D printing or supporting mechanisms, leading to the formation of cold joints.

In both cases, the mechanical properties of the final 3D-printed part are ultimately compromised.

5. Challenges and methods of integrating longitudinal reinforcement

Developing methods to produce reinforced concrete for E-3DCP of complex geometries remains a crucial endeavor [112]. Reinforcement in E-3DCP can be categorized into the following approaches [113]: 1) Post-installed reinforcement: a) reinforcement bars placed and grouted [114–116], b) Prestressed reinforcements [117], c) External reinforcement [118], 2) Pre-installed reinforcement: a) Print around the reinforcement [119,120], b) Print over reinforcements [121,122], 3) Cable entrainment in the filament [123–128], 4) Continuous fiber entrainment [126,129], 5) Overlapping mesh reinforcement [130], 6) Penetrating reinforcement [131–136], 7) Dispersed short fibers [101,137–147], 8) Welded bars [148–152], 9) Printed polymeric reinforcement [153–155].

Despite extensive literature on reinforcement integration in simple geometries, examples of integrating reinforcement in complex parts using E-3DCP are rare. The inherent complexity of these geometries makes it difficult to use standardized methods, particularly for longitudinal reinforcement integration. The existing literature primarily showcases two functions of geometrical complexity in building parts. The first function is pure ornamentation, where the reinforcement does not necessarily need to follow the geometry of the building element. The second type of geometrical complexity is a result of material optimization methods, representing the stresses flow in the building element, and therefore the reinforcement must adhere to the complex geometry.

5.1. Longitudinal reinforcement integration in building parts with ornamental geometrical complexity

In the Concrete Choreography project (Fig. 15a) [6], a series of geometrically reinforced complex columns were introduced. The complexity in this instance served purely as ornamentation, and thus the longitudinal reinforcement did not conform to the complex geometry of the columns. A steel reinforcement cage was post-installed at the center of each column after the completion of the 3D printing process (Fig. 15b). This cage was subsequently connected to a foundation, and concrete was cast in the center of the 3D printed column.

The Tor Alva tower project [156] also exemplifies the use of geometric complexity for ornamental purposes. In this project, voids were strategically incorporated into the design of the complex columns for the 30-m-tall structure. The tower consists of multiple components, each made up of three main structural parts: a precast base, a capital, and E-3DCP columns. These columns feature a hollow channel designed to house reinforcing steel bars that span the entire length of the column. After placement, these channels are filled with grout to secure the bond between the bars and the surrounding concrete. Additionally, the columns (Fig. 15c) utilize post-tensioning techniques, incorporating unbonded stainless steel rods within their hollow cores, as indicated by the red line in (Fig. 15d). The channels for reinforcement are maintained straight at a sloping angle to avoid any deformation of the reinforcing steel bars.

5.2. Longitudinal reinforcement integration in materially optimized complex building parts

Material optimization can be achieved through the use of inherently optimized geometries, such as single-sheet hyperboloid surfaces, as demonstrated by Anton et al. [158]. Each point on these surfaces features two distinct straight lines that lie on the surface. Leveraging this property, Anton et al. [158] engineered hyperbolic columns with cavities aligned along these straight lines, thus eliminating the need for deforming the longitudinal reinforcement (Fig. 16a). Post rationalizing complex geometries is another potential method for simplifying the integration of longitudinal reinforcement. This approach has been

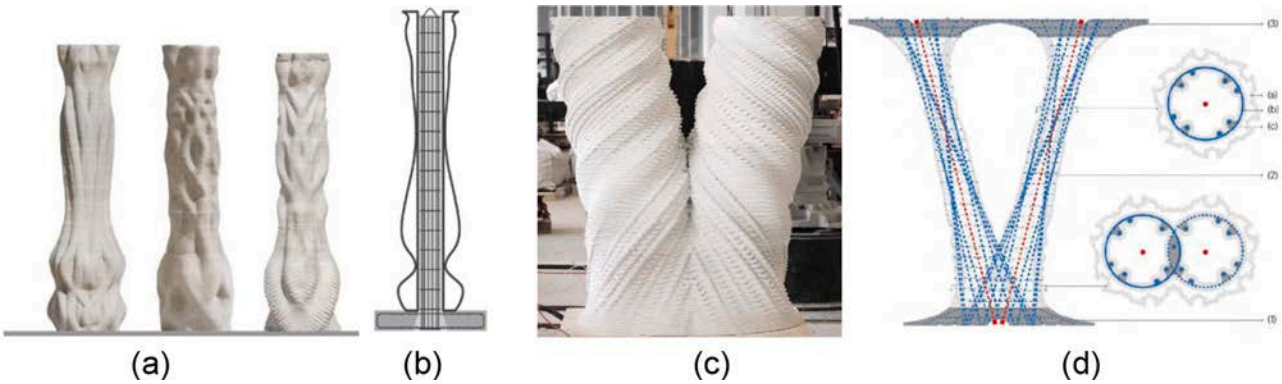

Fig. 15. Longitudinal Reinforcement Integration in Building Parts with Ornamental Geometrical Complexity: a) Example of the Concrete Choreography columns produced [157], b) Integration of a steel reinforcement cage within a column using E-3DCP [6], c) Example of the columns produced for the Tor Alva Project [156], d) Reinforcement placement in the columns [156].

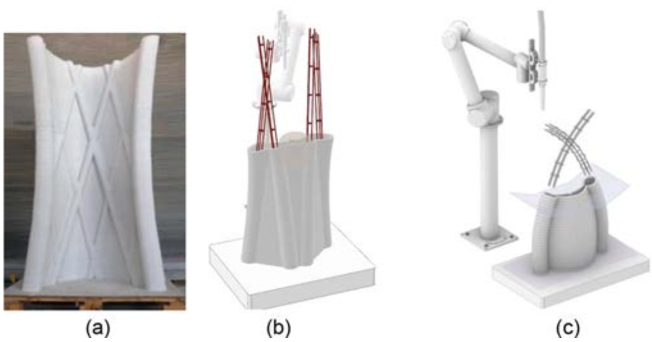

Fig. 16. Methods for integrating reinforcement cages in materially optimized complex parts: a) Engineered hyperbolic column demonstrated by Anton et al. [158], b) Steel reinforcement cage integration in Branch wall [35], c) Steel Reinforcement cage integration in Shell Wall [37].

effectively demonstrated in the Branch Wall project [35], which features a topology-optimized branching wall structure. In this project, the ribs of the structure were post-rationalized into straight sectional cavities. This modification facilitated the installation of straight rebar cages, followed by the casting of concrete into these cavities (Fig. 16b), streamlining the construction process and enhancing structural integrity.

When post-rationalization of complex geometries is not feasible, alternative approaches are necessary. One such method is illustrated in the Shell Wall project [37], which features a complex topology optimized geometry designed to follow the path of stresses. In this instance, post rationalizing the ribs into straight lines would compromise the structural functionality of the part or lead to excessive material use. Therefore, the longitudinal reinforcement in this project needed to conform to the curvature of the complex geometry. To achieve this, the authors discretized the reinforcing cages into shorter segments and then lap spliced them. The accurate placement of the reinforcement steel cages was made possible through the sequential casting while 3D printing method which made sure that the bars stayed in place allowing for the next series of bars to accurately overlap them (Fig. 16c).

Other methods demonstrated in the literature for longitudinal reinforcement of materially optimized complex geometries is the utilization of post tensioning cables, Akbarzadeh et al. [159], Ooms et al. [56], and Vantyghem et al. [51] have demonstrated the utility of this method for integrating longitudinal reinforcement into complex parts. The main advantage of using post tensioning cables is the flexibility that it offers to mimic the geometry of the part, which is demonstrated in (Fig. 17), the main drawback is that compared to regular steel reinforcement bars, post-tensioning with steel cables is more costly, and the cables are more

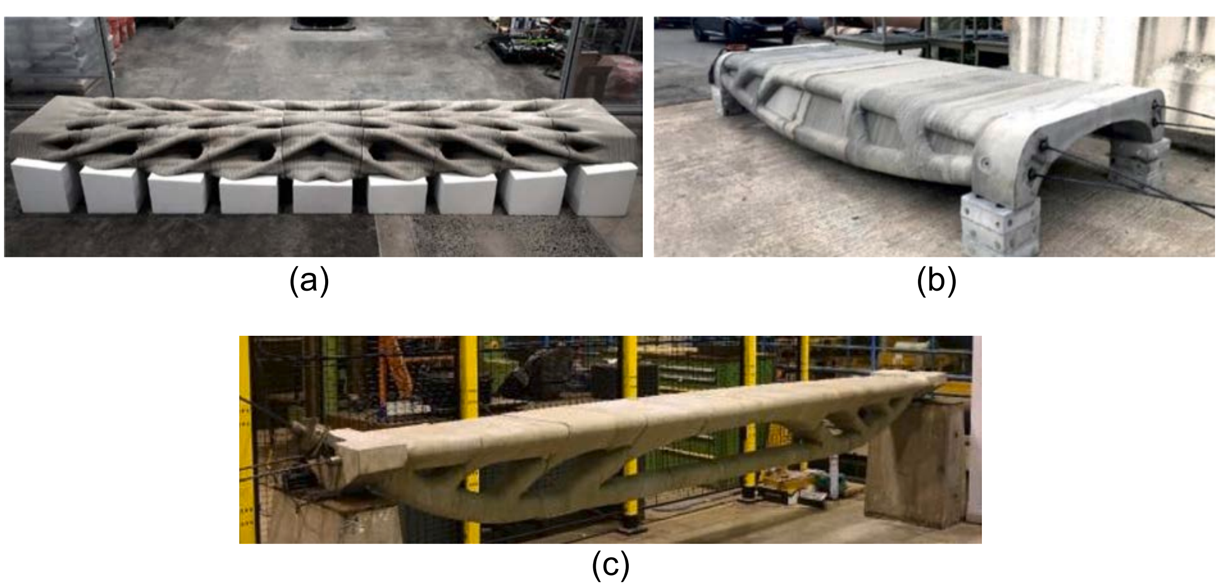

Fig. 17. a) Post-tensioned concrete canopy [159], b) Post-tensioned topology optimized bridge [56], c) Post-tensioned concrete girder designed by topology optimization [51].

susceptible to corrosion.

6. Connections and parts interfaces for complex parts

Connections and interfaces are persistent challenge for reinforced concrete and of paramount importance for the success of parts using E-3DCP [160]. The interfaces and connections between multiple complex components are vital, as they facilitate the effective transmission of loads across the building element, ensuring overall structural integrity. There are two main types of joints between interfaces in E-3DCP a) wet joints [161], where the discrete parts are joined together in a semi-fluid or plastic state, and b) dry joints [162], where the discrete parts are joined together once they are completely set. The existing literature on interfaces for complex parts has primarily been focused on utilizing dry joinery methods.

Anton et al. [163] have investigated the potential of using dry joints and the associated tolerances (Fig. 18a). The authors highlighted that while conventional construction joints require a tolerance of ±10 mm, the tolerances for dry joints are much tighter. Their study produced a column and four identical slab segments, which were later sealed using a 20 mm layer of mortar or a 5 mm layer of silicone (Fig. 18b). The interface feature between the column and the slab is a straight line, which does not necessarily follow the complex part's flow. Despite this, it remains the most commonly used method for discretizing building elements formed of multiple complex parts [51,56,159,164] as it simplifies the design and fabrication process.

An alternative approach demonstrated in the literature involves utilizing complex slicing systems to create interfaces that follow the natural geometry of complex parts [165,166], as shown in (Fig. 18c, d). This method offers a more integrated solution, aligning the interfaces more closely with the parts' intricate geometries, potentially enhancing structural performance and aesthetic integration.

7. Conclusion

In this literature review we have comprehensively presented the techniques and strategies employed in E-3DCP to fabricate complex geometries while mitigating the risk of premature failure. Complexity in the context of the paper refers to geometries that include one or all of the following features: overhangs, cantilevers, and bridges. We discussed the cementitious material properties in relation to the requirements for fabricating these complex geometries and how to navigate these requirements effectively.

One of the primary concerns in E-3DCP is balancing the setting time of concrete. The concrete must be sufficiently fluid to allow smooth pumping and extrusion, yet it must quickly develop static yield strength after extrusion to maintain its shape and buildability. This balance is critical, especially for complex geometries. Techniques such as introducing accelerators and applying heat to accelerate the setting time are useful for achieving this delicate control over the concrete setting. While these methods can enhance buildability, they may negatively impact the long-term mechanical properties and durability of the printed structures as well as introduce complications to the E-3DCP system.

We have also categorized the techniques and approaches for preventing premature failure in E-3DCP of complex geometries into the following three main categories: a) Rationalizing design and slicing strategies to comply with E-3DCP constraints, b) Utilizing support mechanisms, and c) Sequential casting of fast setting concrete while 3D printing. To help the reader navigate this multi objective problem and pick the most appropriate method for their use case, we presented a two-part decision-making framework informed by the material properties and the fabrication methods discussed. Furthermore, the paper has discussed existing methods for integrating longitudinal reinforcement in complex building elements and existing methods for designing connections and parts interfaces.

Future research should focus on automating hybrid processes, such

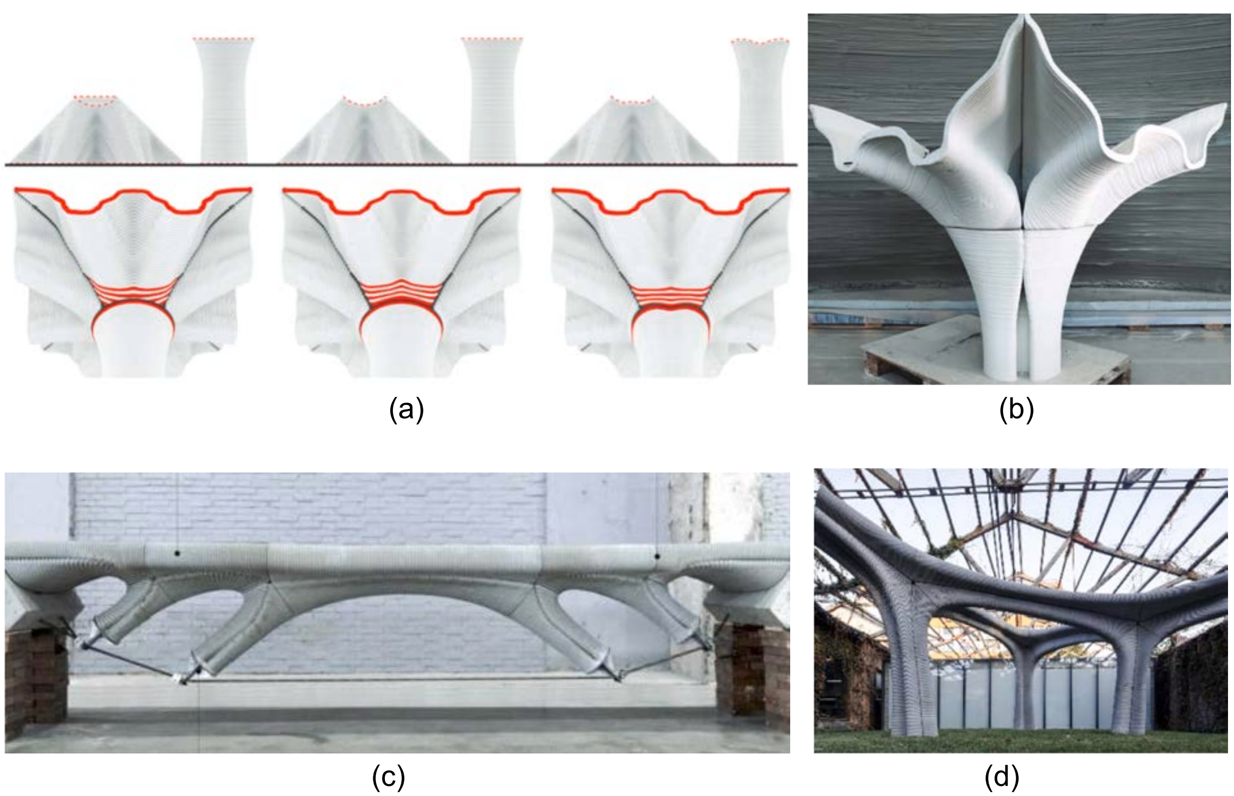

Fig. 18. Interface designs for complex E-3DCP structures a) Design exploration of the parts interface [163], b) Fabricated column to slab interface by Anton et al. [163], c) Interface and assembly of a concrete structure using non-planar slicing system [165], d) Interface design and assembly of a spatial concrete structure using non-planar slicing system [166].

as the sand encasement method, placement of supports, and sequential casting during 3D printing. Automation can significantly enhance efficiency, minimize the risks associated with manual interventions, and reduce interruptions in the E-3DCP process.

Further investigations into methods for automatically integrating longitudinal reinforcement are essential. This includes developing automated systems for the precise placement of steel bars, continuous fiber reinforcement, and other innovative techniques. Additionally, research needs to develop and validate new methods, such as 3D printing metal rebars while using E-3DCP. These methods should provide longitudinal reinforcement with enough flexibility to follow the geometry of complex parts. Designing effective parts interfaces and connections remains a critical area of research. Advanced methods for creating robust, reliable joints between 3D printed elements can ensure the seamless integration of complex geometries into larger structures, enhancing their overall stability and performance.

By addressing these areas, future research can contribute to the development of more efficient, reliable, and versatile E-3DCP technologies, paving the way for broader adoption in the construction industry.

CRediT authorship contribution statement

Abdallah Kamhawi: Writing – review & editing, Writing – original draft, Data curation. **Mania Aghaei Meibodi:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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