short communication
UDC 72.012:004.65
admission date 07 02 2022
approval date 26 12 2024

# TOWARDS CONSTRUCTION OF CUSTOMIZED LARGE-SCALE ARCHITECTURAL ELEMENTS USING 3D PRINTING TECHNOLOGY

## ABSTRACT

Recent advances in computational design and additive manufacturing have impacted the architecture, engineering, and construction industry, requiring a revision of common architectural design practices and processes. Rapid development and usage of digital fabrication, especially 3D Printing (3DP), has enabled the design and construction of more complex forms. This paper reviews different applications of 3DP for the construction of load-bearing architectural elements and the potential and limitations of these approaches. Starting from the hypothesis that 3DP facilitates the production of customized, non-standard, and complex elements, the research question of this paper is: How can the potentials of these technologies be fully exploited? This paper aims to identify relevant publications, collect and systematize 3DP methods, and then gather and analyze the present state-of-the-art in industry, using literature review methodology to illustrate the 3DP technology used in the industry. Relevant projects are then identified and categorized based on the element typology. Next, the advantages and disadvantages of the presented approaches are identified and systematized in relation to the level of design freedom, complexity and customization ability. Finally, the paper proposes a set of strategies for more efficient fabrication of customized architectural elements using 3DP technologies.

Maša Žujović

Faculty of Architecture, University of Belgrade
masa.zujovic@arh.bg.ac.rs

Miodrag Nestorović

Faculty of Architecture, University of Belgrade
enestorm@arh.bg.ac.rs

KEY WORDS
ARCHITECTURAL DESIGN
STRUCTURAL ELEMENTS
3D PRINTING
CONSTRUCTION INDUSTRY
DIGITAL FABRICATION
CUSTOMIZATION

## 1. INTRODUCTION: ARCHIVING THE INTANGIBLE

Computational design first gained popularity in the 1990s, changing the way many architects viewed the design process. The transition to 3D models of representation enabled designers to create free-form spaces with a level of geometric depth and complexity that has never been seen before. Since computational design has no economy of scale, meaning that the price isn't dependent on the total number of objects created or the number of variations, designers came to the idea of mass-customization. This meant that there was a possibility of using digital tools to mass-produce variations at no extra cost. This idea evolved over the past decades, and now, what Carpo[1] has referred to as the Second Digital Turn demands the revision of standard procedures and methods for architectural design. The development of computational design tools has opened up opportunities for designing more sustainable and optimized structures with outstanding geometric freedom. Meanwhile, recent advancements in additive manufacturing (AM), processes based on creating objects from digital data by adding material in successive layers, better known as 3D Printing (3DP)[2], have enabled the fabrication of such designs. Starting from the hypothesis that 3DP facilitates the production of customized, non-standard, and complex elements, the research question of this paper is: How can the potentials of these technologies be fully exploited?

This paper reviews different applications of 3DP for the construction of load-bearing architectural elements and the potential and limitations of these approaches. Many authors focus on the development of this technology, but their research is often focused on the advancement of technology through solving technical challenges, rarely prioritizing the design processes. As a result, many commercially available solutions for 3DP of architectural elements produce results that do not exemplify the geometric complexity of structural optimization but rather focus on the cost-time optimization of built structures[3]. Consequently, such examples were excluded from this research. Examples of 3DP large-scale architectural elements can more often be found in academia than in practice, with many research groups working in collaboration with companies to further develop project-specific technologies and fabrication methods[4].

The goal of this paper is to collect and systematically analyze the current state of the art by assessing the advantages and disadvantages of presented approaches and their relation to the level of design freedom, complexity and customization ability. A systematic literature review method was used to collect, analyze, and synthesize a selected body of research on the subject in order to answer the research questions and create new perspectives and frameworks.
A variety of sources, including the internet and other sources, were examined to acquire a complete picture of the state of the art in the field since it was thought that integrating non-scientific sources would provide a more comprehensive overview. Primarily, data collection was done by searching two main databases, Web of Science (WOS) and Scopus, using topic-relevant keywords. The search was only limited to the English language, and the publication period spanning ten years, as this timeframe was determined to be the most relevant for this study.

The analysis was conducted as a three-part process. First, current 3DP methods and technologies were identified. Next, methods and technologies used in those projects were systematized in order to determine their potential and challenges. Secondly, a wide range of projects was identified to recognize current trends and development directions in the industry. Finally, prominent research organizations and companies were recognized along with the most relevant research projects at the moment. Next, based on the literature review results, the potentials and limitations of different 3DP methods were observed and summarized. The results were then used to form a framework for more efficient design and fabrication of customized architectural elements using 3DP technologies.



## 2. LARGE-SCALE ADDITIVE MANUFACTURING IN AEC

Additive manufacturing, specifically 3DP technology, has been developing since the mid-1980s[5] and was introduced in the architecture, engineering, and construction industry (AEC) with the development of the first large-scale cement-based printer patented by Joseph Pegna in the late 1990s[6]. Even though 3DP refers to several AM processes, the most commonly used methods in the construction industry can be grouped into two main categories (1) Material Deposition Method (MDM) and (2) Binder-jetting (BJ)[7]. An overview of the methods discussed, as well as their properties and applications, can be found in *Table 1*.

| | Method | Application | Structural Properties | Location | Materials |
|---|---|---|---|---|---|
| MDM | CC | Housing units, Walls | Load-bearing | On-site | Concrete, Ceramics |
| | 3DCP | Structural elements, Panels | Load-bearing | Prefabrication | Concrete |
| | FDM | Building blocks, Panels, Formwork fabrication | Load-bearing | Prefabrication | Ceramics, Glass, Polymers |
| BJ | D-Shape | Walls, Panels, Formwork fabrication | Load-bearing | On-site, Prefabrication | Sandstone |
| | 3DP | Formwork and mould fabrication | Not Load-bearing | Prefabrication | Sandstone, Ceramics, Polymers, Metals |

TABLE 1: Overview of the main 3DP methods in AEC

### 2.1 Material Deposition Method

MDM is a layer-based method in which materials are extruded by a nozzle in layers on a predefined path, and then the material solidifies, creating the object. The two best-known MDM methods are Contour Crafting (CC) and 3D Concrete printing (3DCP)[8].

CC is an AM technology invented by Khoshnevis in 1998[9]. The technology was specifically designed for on-site construction. Despite their long development, on-site 3DP technologies still have a lot of limitations. The scale of the projects using this technology is still limited in size and possible geometric complexity that can be achieved[10]. Some companies have developed technologies similar to CC that are capable of 3DP entire housing units. For instance, there are printers that can produce construction elements at full scale, but unlike standard CC these methods are based on prefabrication[11].

3DCP is another extrusion-based method, but the main difference is that, unlike CC, this technology was designed for the prefabrication of concrete elements. The geometric complexity is limited by a maximal overhang that can be achieved using selected materials. As such it is more suitable for printing vertical non-standard architectural elements, especially columns or walls[12] Compared to CC, this method provides more geometric freedom, with the downside being a bigger layer height. This results in a coarser ribbed surface finish, where post-processing might be necessary, and weakening of the material's structural properties.

Another commonly used extrusion-based method is Fused Deposit Modelling (FDM), where the state of the material is controlled by a temperature difference. This technology can be used with different materials such as plastic, clay or ceramics and is often used for printing large-scale formworks[13].

### 2.2 Binder-jetting methods

BJ is a powder-based method where the liquid binder is selectively applied in thin layers over a thin layer of powder to create objects. The most common and well-known BJ method is D-shape printing developed by architect Enrico Dini[14]. Its significant advantages over MDM are its high printing resolution, almost complete geometric freedom, no need for support structures and large building volume[15]. This method of 3DP doesn't require any additional support structures, but powder serves as both; this allows the fabrication of complex geometries with a high level of detail. On the other hand, the disadvantage of this process is that it often requires postprocessing steps for cleaning loose powder and stabilizing the printed parts, which can be time-consuming[16]. The D-shape printer uses cement and can be used for printing large-scale architectural elements both on-site and prefabricated.

Three-Dimensional Printing (3DP) is a powder-based AM method that is able to print any powder material that can react with a liquid binder like cement, plastics or ceramics[17] Sand-printing, one of the 3DP techniques, has qualities that make it appropriate for fabricating architectural components, as it enables the manufacturing of precise and high-resolution large-scale parts. However, this technology still needs to be successfully applied for the fabrication of full-scale architectural elements due to the low structural strength of the sand-based 3D-printed material. For this reason, 3DP is more often used for printing formworks for non-standard structural concrete elements. A systematized overview of the discussed 3DP methods' limitations and potentials is presented in *Table 2*.

| Method | Limitations | Potentials |
|---|---|---|
| **CC** | • Print size limited by the span of the printer<br>• Intended only for on-site fabrication<br>• Geometric complexity | • Small layer height<br>• Good surface finish resolution<br>• Used for load-baring elements |
| **3DCP** | • High layer height<br>• Low surface finish resolution<br>• Presence of cold bridges between layers<br>• Geometric complexity limited by overhang angle | • Intended for prefabrication,<br>• Suitable for printing vertical elements<br>• Used for load-baring structural elements |
| **FDM** | • Usually used for small-scale objects<br>• Requires support structure<br>• Slow printing speed<br>• Requires post-processing | • Suitable for formwork printing<br>• High surface finish resolution<br>• Uses wide selection of materials<br>• Commonly available technology |
| **D-Shape** | • Post-processing of material needed<br>• Structural performance of the printed element<br>• Slow printing speed | • Good surface finish resolution<br>• Greater form complexity |
| **3DP** | • No load-bearing properties<br>• Post-processing of material needed | • Suitable for formwork printing<br>• Uses wide selection of materials<br>• Very high surface finish resolution<br>• Scalable to larger build volumes |

TABLE 2: Summary of the Characteristics of 3DP Methods

## 3. 3DP TECHNOLOGY APPLICATION OVERVIEW IN AEC

A significant number of projects focusing on the application of 3DP technology in the AEC industry were identified through the literature review. 3DP is currently used in a wide range of projects, from housing units[18] to space outposts[19] applied for both on-site and prefabricated elements. As this research focuses on customized architectural elements on-site technologies used for the fabrication of entire buildings are disregarded because of the limitations in terms of project scale and geometric complexity, focusing on prefabrication methods. Prefabrication is deemed more suitable for the fabrication of custom elements as it allows mass customization of large-scale architectural elements.

Regarding the variety of materials used for printing, it was observed that although there are studies based on the application of other materials, such as metal[20], concrete is the most commonly used structural material. As already mentioned, computational design tools allow complete design freedom in terms of geometric complexity and structural and material optimization of elements. However, in practice, most concrete structural elements are solid volumes, either linear (beams or columns) or planar (slabs). This is because the production cost increases with complexity, and materially optimized elements typically need unique formwork solutions, making them cost-inefficient as formwork can add up to 75% of construction cost[21]. One of the consequences of the broad application of concrete is its negative impact on the environment. Its carbon footprint is significant on a global scale, with 5% of the global $CO_2$ output[22] For this reason, a common goal of reviewed projects was raising sustainability through the reduced use of material and the need for formworks when using 3DP technology to produce bespoke elements.

### 3.1 Use of 3DP in bridge construction

Although bridges are not structural elements in architecture, they are specific structures that have the potential to develop and test new 3DP methods. Their freedom of design and necessary structural characteristics make them one of the most researched full-scale structures. This typology is important because it demonstrates that the application of 3DP technology is possible on larger scales and that it can meet construction industry regulations. This is something that is yet to be reached when implementing 3DP structural elements in full-scale architectural projects.

Loughborough University constructed Footbridge in Madrid[23] (*Figure 1*) assembled from U-shaped 3DP concrete elements that meet all state requirements defined for this structural typology.

Another notable example is the bicycle bridge from TU Eindhoven in 2017[24] (*Figure 2*). The bridge demonstrates the viability and security of 3DP concrete structures for public usage. TU Eindhoven later developed the largest 3DP bridge to date in Nijmegen, Netherlands, using similar technology[25]. This bridge also demonstrates advancements towards more complex geometric designs compared to the previous projects (*Figure 3*). To avoid the need for additional reinforcements the bridges are often designed as compression-only structures and divided into printable segments that are prefabricated and assembled on-site using concrete 3DP. Baoshan Pedestrian Bridge[26] from Tsinghua University is one such project (*Figure 4*). The project effectively demonstrates how 3DP has made it possible to produce materially efficient elements. Another example of a compression-only structure is the Striatus Bridge[27], a joint project between ETH Zürich and Zaha Hadid Architects (*Figure 5*).

FIGURE 1: Footbridge in Madrid, https://iaac.net/wp-content/uploads/2016/12/Puente-3D-002-1024x682.jpg, accessed on 09.06.2022

FIGURE 2: TU Eindhoven Bicycle bridge, Salet, Theo A. M., Zeeshan Y. Ahmed, Freek P. Bos, and Hans L. M. Laagland. "Design of a 3D Printed Concrete Bridge by Testing." Virtual and Physical Prototyping 13, no. 3 (July 3, 2018), 234, figure 20



As each type of architectural element poses its own challenges during the design and manufacturing process most researchers focus on a specific type of element. Used technology and design principles tend to be project-specific, and fabricated designs are often prototypes that are still to be implemented in real-life architectural projects. Consequently, to assess the advantages and disadvantages of available 3DP methods, this review focuses on the systematization of projects based on structural element typology and the classification of AM methods used in these projects.

FIGURE 3: Bridge in Nijmegen, Photo by Municipality of Nijmegen, https://assets.eu-central.w3.tue.nl/w/fileadmin/_processed_/e/6/csm_3d1_89ed9953ae.jpg, accessed on 07.12.2022

FIGURE 4: Baoshan Pedestrian Bridge, Photo by Professor Xu Weiguo, https://www.archdaily.com/909534/worlds-largest-3d-printed-concrete-pedestrian-bridge-completed-in-china/5c3f4e1b284dd125fd000102-worlds-largest-3d-printed-concrete-pedestrian-bridge-completed-in-china-photo, accessed on 07.12.2022

FIGURE 5: Striatus Bridge, Photo by Chiara Becattini, https://www.domusweb.it/content/dam/domusweb/it/architecture/gallery/2021/07/26/shajay-bhooshan-zaha-hadid-architects-striatus-bridge/gallery/domus_striatus_bridge_6.jpg.foto.rmedium.png, accessed on 07.12.2022

## 4. 3DP TECHNOLOGY APPLICATION IN THE CONSTRUCTION OF ARCHITECTURAL ELEMENT

Based on the literature review findings, discrete structural elements explored in this paper can be divided into four categories: (1) columns, (2) beams, (3) slabs and (4) construction blocks. There are two main approaches to applying 3DP for geometrically complex forms: the printing of formworks or the printing of structural material, which can be seen in all categories.

### 4.1 Columns

The most researched group of structural elements are columns. As columns usually carry compression loads, concrete is often a suitable material for their fabrication. However, because of their formwork complexity, columns are rarely made as bespoke elements but rather as simple forms with often uniform cross-sections. For that reason, many research projects focus on 3DP concrete as a method for fabricating geometrically complex columns that can be structurally optimized.

Most of the research still focuses on prototypes with only a few examples of their application in full-scale architectural projects as structural elements. The Future Tree pavilion project by ETH Zürich and Xtree company is one of the examples of the full-scale structural column projects[28]. This pavilion is a result of preceding Branching Column and Twisting Column projects as well as several prototypes (*Figure 6*). These projects are using Eggshell technology, a formwork printing approach with simultaneous digital concrete casting where a thin plastic outer shell is printed using FDM 3DP and later removed from the hardened concrete.

FIGURE 6: Columns printed using Egshell technology, Burger, Joris, Ena Lloret-Fritschi, Fabio Scotto, Thibault Demoulin, Lukas Gebhard, Jaime Mata-Falcón, Fabio Gramazio, Matthias Kohler, and Robert J. Flatt. "Eggshell: Ultra-Thin Three-Dimensional Printed Formwork for Concrete Structures." 3D Printing and Additive Manufacturing 7, no. 2 (April 1, 2020), 55-56, figures 5-6,8

This method allows for complex forms with a high-resolution surface finish. Scaling up a prototype for use in construction revealed one limitation, as reinforcement placement limits the possibility of cross-section variations.

The idea of 3DP formwork was tested in a few more ETH research projects, resulting in successful prototype structures. A similar approach to Eggshell was used in the Free Formwork project also by ETH Zürich[29] where BJ and FDM 3DP are combined to create a thin flexible outer shell that can be peeled off the cured concrete. Concrete with steel reinforcement cage is replaced by casted concrete[30]. Another approach was tested in Dissolvable Formwork[31] and Additive Archetypes[32] projects by casting concrete into FDM 3DP formworks made of water-soluble material. However, there have yet to be examples of the application of these technologies in architectural projects.

FIGURE 7: Concrete Choreography Project, source: https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2019/06/fabrication-setup-1.

On the other hand, the printing of the structural material rather than formwork on a large scale can be seen in the Concrete Choreography project from ETH[33] (*Figure 7*). In this research, 3DCP was used as both formwork and structural material; the printed structure was later reinforced and filled with cast concrete. A series of twelve three-meter-tall columns were designed for a performing arts festival. The accent was put on the exploration of design possibilities using selected technology. Krypton project from XTree and Marc Dalibard also uses 3DP concrete as lost formwork for a column built in France[34].

There are also research projects focusing on the use of 3DP for the fabrication of column structures by printing structural materials with no additional support or formwork. A fossilized project from Bartlett combines 3DCP and BJ technology to explore the fabrication of complex forms.

The project focuses more on the design process and achieving form complexity using 3DP technology rather than on the structural properties of designed columns[35]. 3D printing Architectural expression[36] is another project developed as a part of the design studio at TU Eindhoven featuring three 3m high column prototypes. Cornell University led the project exploring the application of 3DP for architectural elements, especially columns in the Additive Architectural Elements project[37].

There are also researches focusing on materials other than concrete, one of them being metal 3DP led by Bologna University and company MX3D, although this technology still hasn't been tested in full-scale prototypes[38]. Another research by Blast Studio is exploring the use of live mycelium as a structural material for 3DP columns[39].

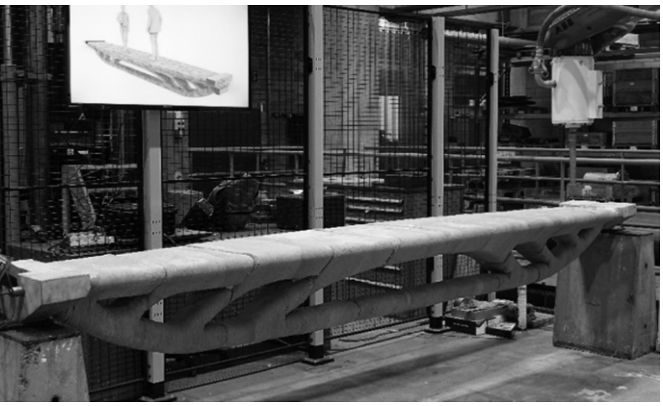

FIGURE 8
Ghent University Post-Tensioned Concrete Girder, Vantyghem, Gieljan, Wouter De Corte, Emad Shakour, and Oded Amir. "3D Printing of a Post-Tensioned Concrete Girder Designed by Topology Optimization." Automation in Construction 112 (April 2020), 7, figure 9

FIGURE 9
3D Printed Reinforced Beam from ETH Zürich, https://dbt.arch.ethz.ch/project/3d-printed-reinforced-beam/, accessed on 27.07.2022

FIGURE 10
COEBRO Ribbed Slab, Hansemann, Georg, Robert Schmidt, Holzinger Christoph, and Joshua Tapley. "Additive Fabrication of Concrete Elements by Robots: Lightweight Concrete Ceiling." In Fabricate 2020, 124–29. UCL Press, 129, figure 8

### 4.2 Beams

The beams are one of the least researched elements due to their more complex loads compared to columns, but also because they can be integrated into slab design, reducing the need for a beam as a structural element. However, there are two notable research projects focusing on beam fabrication. The first is Post-Tensioned Concrete Girder from Ghent University and company Vertico[40] (*Figure 8*). The project aimed to demonstrate how topological design paired with 3DCP can create a material-efficient structure. Topology optimization tools were used for form-finding during the design process. After the optimization pattern was created, the form was converted to the 3D structure. The prototype girder with a span of 4m was produced using 3DCP and it consists of eighteen prefabricated segments two end blocks that would need to be cast on site.

The second research is 3D Printed Reinforced Beam from ETH Zürich, which uses BJ technology to print topologically optimized beams in the sand (*Figure 9*). The beam has a complex geometric pattern and has been printed in seven segments with a 4.5m span[41]. There have yet to be any other prototypes from this research to show if scaling up the element to full architectural scale is possible using this technology and if the sand can be fully used as a structural material for larger spans.

### 4.3 Slabs

Although more materially efficient than solid, optimized ribbed slabs lost their popularity in architectural practice in the second half of the last century because of the high cost of formworks when they are not applied as a modular element.  The same problem persists today, making bespoke slab design fabrication a point of interest for several researchers. One of the main reasons for researching optimized slabs is the possibility of better structural performance, material efficiency, and design aesthetics. Also, service ducts such as ventilation, heating or fire sprinklers can be integrated into the design eliminating the need for suspended ceilings[42].

COEBRO[43] project from TU Gratz uses 3DCP for the prefabrication of the optimized ribbed slab. Concrete elements were printed, then reinforcements were placed between the elements, and concrete was cast on top (*Figure 10*). The use of concrete as built-in formwork eliminates the need for a large number of different formwork pieces, which traditionally represent the biggest limitation in the production of ribbed slabs, and enables efficient construction. This way, 3DP concrete can be seen on the bottom side of the slab, and it has specific aesthetic qualities.

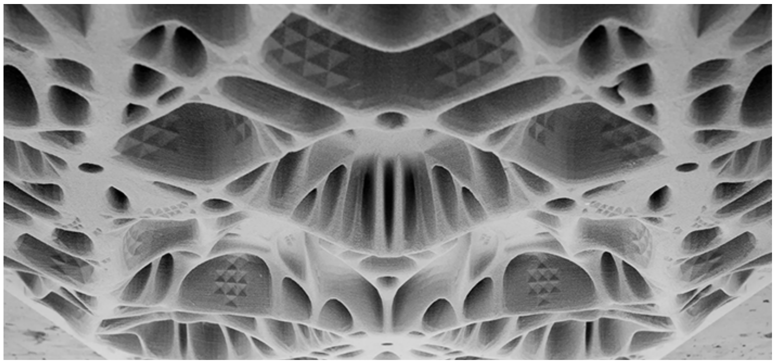

FIGURE 11A:
3D Printed Slab Project, source: https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2018/02/dbt-eth-Topology-Optimization-for-3D-Printed-Slabs-andrei-jipa-mathias-bernhard-0.jpg?fit=3840%2C1645, accessed on 27.07.2022.

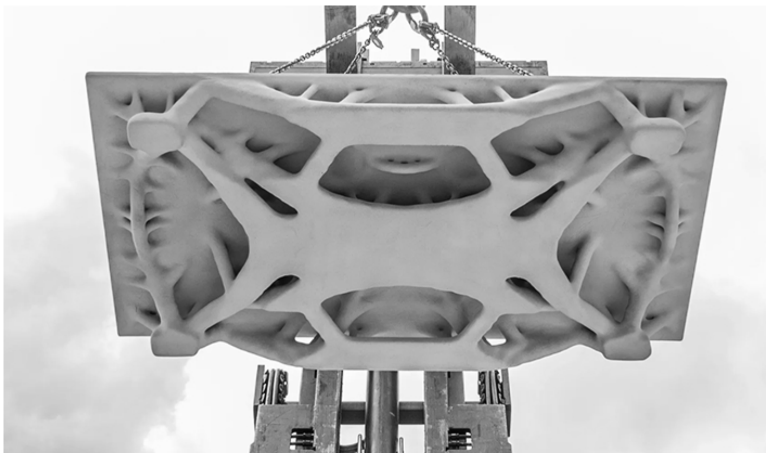

FIGURE 11B:
Topology Optimisation for a Concrete Slab Project, source: https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2018/02/dbt-eth-Topology-Optimization-for-3D-Printed-Formwork-andrei-jipa-mathias-bernhard-0.jpg?w=1920&ssl=1, accessed on 27.07.2022.

ETH Zürich realized a series of projects during recent years developing structurally optimized slabs. 3D Printed Slab[44] explored the possibilities of using topology optimization as a design method for floor elements. This research focused on achieving a high level of detail of surface geometry. As a result, a 2 m$^2$ prototype was printed using sand printing (*Figure 11* (a)). Scaling up of the prototype was done through Topology Optimisation for a Concrete Slab[45] project where sand 3DP was instead used for formworks that were later filled with conventionally cast concrete. This method was tested on a smaller-scale demonstrator slab (*Figure 11* (b)). These two projects were further developed through the Smart Slab[46] project. Sand 3DP formwork was used in combination with concrete casting and spraying to produce a complex non-standard ribbed slab with highly detailed geometry. This is the only project tested on an architectural scale as part of the DFAB HOUSE, where eleven 7.4m long segments were joined into a single prefabricated slab (*Figure 12*). This time, post-tensioning ducts and electrical and sprinkler systems were integrated into the slab structure.

Funicular Floor[47] and Fast Complexity[48] projects from ETH are also combining structural optimization with the integration of functional elements into the design. The Funicular Floor uses a 3DP for formwork elements on top of which are placed reinforcements and cast concrete. The usage of 3DP formwork results in a highly detailed surface where the cooling and heating systems are integrated inside the voids in the structure. This design method can result in a 70% reduction of concrete compared to the standard monolithic slab. Fast Complexity addresses the issue seen in previous projects such as Smart Slab where multiple different fabrication methods are used to manufacture a single element. The project proposes a combination of the BJ method for formwork and 3DCP extrusion for the loadbearing part directly on top, as BJ gives precision and 3DCP speed. The proposed method was tested on a 2 $m^2$ prototype, representing a 1:1 excerpt of a larger slab. The structure is divided into modules of reusable BJ 3DP formwork with extruded 3DP concrete on top of it. The structure above can differ for each module, allowing for structural optimization and integration of functional elements (*Figure 13*). Also, after removing the formwork, only the bottom side has a high-resolution surface finish, while the other sides have a coarser finish, as there is no need for a detailed finish on all sides of the slab.

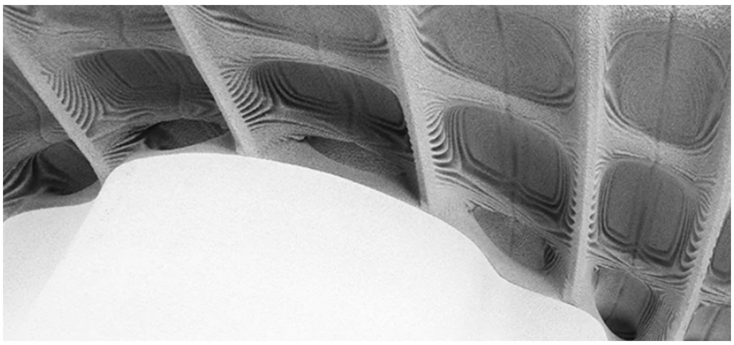

FIGURE 12: Smart Slab Project, https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2018/06/DBT_NEST_DFAB_HOUSE_ETH_EMPA_Smart_Slab_005b.jpg, accessed on 27.07.2022

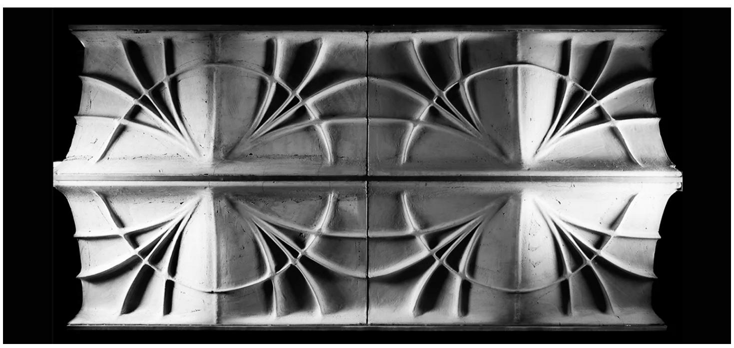

FIGURE 13: Fast Complexity Project, https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2020/06/Fast-Complexity_7.jpg?w=1280&ssl=1, accessed on 27.07.2022

### 4.4 Construction Blocks

The final group of elements are construction blocks prefabricated using AM technologies. While most research focuses on large-scale 3DP for building elements, some authors directed their research towards the discretization of elements by using 3DP for small-scale building blocks. Building Bytes[49] project explored the use of small-scale 3DP ceramic printing for non-standard construction blocks, customized with variable characteristics and shapes that can be used as façade components or structural elements (*Figure 14*). The study explores ceramic brick formations with irregular three-dimensional features and interlocking joints. With this method, it is possible to include the essential mechanical or electrical infrastructures inside the bricks. This type of construction block still hasn't been tested in full-scale construction, only as part of outdoor installations or interior screens. Another research project with a similar approach is Digital Adobe from IAAC[50]. The main goal of the research was to produce architectural solutions using AM technologies and natural materials. Local clay is used as 3DP material for interlocking blocks. This was tested on a series of smaller-scale prototypes before building full-scale prototypes in an attempt to test the possibilities of its use in architectural objects. The test structure was a self-standing clay wall made of 3DP blocks (*Figure 15*). Modular 3DP blocks were further explored in Knitting Concrete[51] research by KTH Royal Institute of Technology and company XTree. In this case, concrete is used as a material for 3DP, and the main goal of the research was to create a database of different toolpath patterns for printing concrete when designing architectural elements.

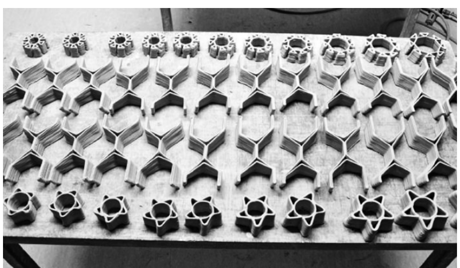

FIGURE 14:
Building Bytes Project, Peters, Brian. "Building Bytes: 3D-Printed Bricks," 2013., 115, figure 6



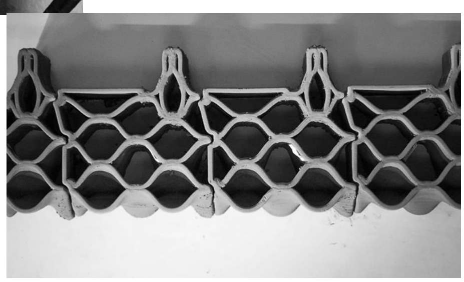

FIGURE 15:
Digital Adobe Project, https://iaac.net/wp-content/uploads/2019/03/09-prototype-09.jpg, accessed on 27.07.2022

Depending on a pattern, the element can have different surface qualities and aesthetic properties, or it can change its structural properties. Several patterns were tested on different scales and full-scale prototypes were produced by XTree company.

## 5. RESEARCH PROJECTS

Analysis showed that research projects focused on the design of custom prefabricated elements are currently primarily done in the academic setting. Currently, the most significant percentage of projects is being developed by Digital Building Technologies at ETH Zürich. Additionally, ETH has built a full-scale test building where they have implemented several researched AM methods for fabricating 3DP elements including a prefabricated Smart Slab system. TU Eindhoven is another research center that has left had a significant impact in the field of prefabricated 3DP elements in recent years, although their research is mainly focused on the development of bridge structures with only a few projects relating to structural elements used in architecture. In addition to academic research, another important factor that contributes to progress are construction companies, which often partner with academia to further develop AM technology. *Table 3* provides a comprehensive summary of all reviewed projects. It maps each project according to the element typology, name of the project, institutions and category of the 3DP system.

| Element type | Project | Participants | Method |
|---|---|---|---|
| Column | Concrete Choreography[52] | ETH Zürich | 3DCP |
| | 3D printing Architectural expression[53] | TU Eindhoven + Vertico | BJ (D-shape) |
| | The Future Tree[54] | ETH Zürich + XTree | FDM |
| | Branching Column, Twisting Column[55] | ETH Zürich + XTree | FDM |
| | WAAM Columns[56] | Bologna University + MX3D | Metal 3DP |
| | Fossilized project[57] | UCL Bartlett | 3DCP + BJ (D-shape) |
| | Free Formwork[58] | ETH Zürich | BJ + FDM |
| | Additive Archetypes[59] | ETH Zürich | FDM |
| | Dissolvable Formwork[60] | ETH Zürich | FDM |
| | Krypton[61] | XTree + Marc Dalibard | CC |
| Beam | Post-tensioned concrete girder[62] | Ghent University + Vertico | 3DCP |
| | 3D-printed reinforced beam[63] | ETH Zürich | BJ |
| Slab | Fast Complexity[64] | ETH Zürich | BJ + 3DCP |
| | COEBRO[65] | TU Gratz | 3DCP |
| | 3D printed slab and Topology Optimisation For A Concrete Slab[66] | ETH Zürich | BJ (Sand-printing) |
| | Smart Slab[67] | ETH Zürich | BJ (Sand-printing) |
| | Funicular Floor[68] | ETH Zürich | FDM |
| Construction Blocks | Knitting Concrete[69] | KTH Royal Institute of Technology + XTree | 3DCP |
| | Building Bytes[70] | DesignLab Workshop | FDM (Ceramics 3DP) |
| | Digital Adobe[71] | IAAC | FDM (Clay 3DP) |

TABLE 3: Comprehensive summary of all reviewed projects

## 6. DISCUSSIONS

### 6.1 Potentials and Limitations in Fabrication of 3DP Architectural Elements

This part of the paper presents a systematized overview of the detected challenges and potentials related to the design and fabrication processes of selected element typologies based on the literature review findings, as presented in *Table 4*.

| Element type | Challenges | Potentials |
|---|---|---|
| *Column* | • Reinforcement integration<br>• Difficult to achieve necessary structural properties<br>• Design scaling up<br>• Building codes requirements | • Geometric complexity and aesthetic qualities<br>• 3DP used for structural material or formwork<br>• Different methods and materials are researched |
| *Beam* | • Reinforcement integration<br>• Limited research<br>• Obsolete as a prefabricated element<br>• Difficult to achieve necessary structural properties<br>• Requires element discretization | • Form optimization for material efficiency<br>• Use of 3DP structural material |
| *Slab* | • Reinforcement integration<br>• Complex case-specific loads<br>• Multiple fabrication methods needed per element<br>• Requires element discretization<br>• Design scaling up<br>• Building codes requirements | • Geometric complexity and aesthetic qualities<br>• Form optimization for material efficiency<br>• 3DP used for structural material or formwork<br>• Integration of infrastructure ducts<br>• Possible high surface finish resolution<br>• Formwork design and production |
| *Construction Blocks* | • Limited research<br>• Limited structural performance<br>• Fabrication time | • Geometric complexity and aesthetic qualities<br>• Material efficiency<br>• Use of local materials<br>• Wall and panel design<br>• Use of small-scale equipment |

TABLE 4: Summary of potentials and challenges in the fabrication of 3DP architectural elements



All of the discussed element types have limitations in terms of reinforcement integration, which affects the choice of the 3DP method and the geometric complexity of the design. Another common limitation is the need for the practical testing of the designed models, as building codes generally don't recognize 3DP fabrication methods and custom designs. Despite said limitations, research shows a great potential for the reducing of the material consumption thus lowering of $CO_2$ emission for concrete structures through the use of the 3DP methods and form optimization, especially for the 3DP slabs.

Research showed that even if not yet at full-scale 3DP is a suitable technology to consider for the fabrication of all of the analyzed structural elements in non-standard geometries.

By using 3DP methods it is possible to fabricate custom elements with optimized forms without the need for traditional formworks making this process much more time-cost efficient. However, the biggest problem is encountered when trying to scale up the prototypes to architectural scale. Another significant challenge across all categories is fabricated elements' structural properties. The structural properties are dependent on two factors: applied AM methods and used material. As was previously shown each technology has its weaknesses in terms of the structural properties of the end product. Limitations in structural strength and aesthetic qualities can be mediated by improving material properties and choosing the most suitable fabrication method. However, further research is still needed in both areas to substantially improve the current state of 3DP technology.

### 6.2 Strategies for optimizing the construction of customized architectural elements

Taking into the account said limitations of currently available technology, this paper proposes a strategy for more efficient design and fabrication of customized architectural elements. Computational design tools allow us to create complex optimised forms; however, the limitations set by the technology must be taken into account to form the most efficient process. This chapter discusses several strategies whose implementation can optimize the design process of architectural elements so that it integrates the potentials and limitations imposed by technology.

**1 Design by Testing Implementation**

Based on the literature review, it can be concluded that optimization tools must be used from the early stages of the design process to achieve structurally efficient constructions. Namely, topology optimisation has shown great potential, especially in slab design as it allows optimised material distribution leaving room for the integration of other functional elements inside the structure. Design and fabrication need to be part of a single process that cycles between the two phases iteratively. Since most national construction standards do not yet recognize 3DP fabrication, one option is to use design by testing to construct full-scale structures, demonstrating their ability to adhere to legal criteria, ensuring the possibility of their application in standard practice.
This method can be seen in the Smart Slab project, which was the result of

several separate types of research where developed prototypes t focused on different aspects of the application of the technology and which results served as input parameters for each subsequent step, up to the final slab model that could be implemented in a real-life setting.

**2 Using the prefabrication methods**

Analysis of different large-scale 3DP methods' potentials and limitations confirmed that the use of prefabrication methods is a more suitable approach to mass customization than any currently available on-site fabrication method. CC and other similar methods used for on-site 3DP, proved to be too limiting for exploring the full potential of digitally designed forms. Such technology is limited both in terms of the size and complexity of an element that can be achieved. For this reason, other technologies, such as BJ or 3DCP, are more suitable for the direct printing of architectural elements. Demonstration of these limitations can be found in projects of 3DP houses and are discussed in the article. Approaching 3DP technology as a tool for prefabrication would realize one of the main potentials of this technology, which is the possibility of producing variations without the additional costs that are characteristic of standard prefabrication methods. That is why 3D printing can be seen as the next step in the development of twentieth century prefabrication methods.

**3 Printing Formworks**

Even though the printing of architectural elements can be achieved by directly printing structural material using MDM methods, there are still limitations regarding the structural and aesthetic characteristics of such printed structures. For this reason, the proposed approach for more efficient fabrication of full-scale structural elements is printing formworks and not the element itself, or at least the combination of the two approaches. This approach allows for a much greater potential for achieving geometric complexity as a result of optimisation procedures, as can be seen in the number of analysed slab projects from ETH Zürich, where 3D sand printing was used in combination with classical concrete pouring methods. Another example of this approach is the Eggshell system, in which the application was tested on a full scale. Aside from geometric complexity, this approach results in a smoother and more detailed surface finish, opening new design possibilities. Finally, printing formworks, either removable or staying in place, enables the application of structural materials in more traditional ways to accomplish higher structural strengths. At the present moment, the authors consider this approach to have the highest potential to fully exploit the benefits of both computational designs and AM fabrication processes to produce custom architectural elements efficiently.

## 7 CONCLUSIONS

This paper offers a systematic state-of-the-art review of current modes of 3DP technology application for the fabrication of large-scale architectural elements. Following the research goal, various possibilities for applying 3DP technology in the construction industry have been identified and presented. The different types of available 3D printing methods are also identified and analysed to gain insight into their potential and shortcomings. Next, selected projects were systematized based on the typology of the element, through which potentials and challenges relating to each project and the specific use of fabrication methods were assessed.

Based on the literature review results and identified challenges, this paper proposes a set of strategies for more efficient design and production of structural elements through the use of 3DP technology. By putting it into practice, the potential of 3D printing would be realized. The proposed strategies address the entire production process by proposing the integration of design and fabrication processes. They also discuss the approaches to 3DP that authors consider to have the most potential for use with mass-customized structural elements. The proposed framework is intended as a guideline and possible directions for further research which should focus on integrating proposed design strategies and their practical testing. This paper doesn't address one of the main challenges present with all 3DP methods: the printed element's structural and material properties. Because of that, future research is still needed to improve structural qualities through material research or modification of the 3DP methods for 3DP structural elements to become more commonly used in large-scale projects.

## NOTES

1 Carpo, *The Second Digital Turn: Design Beyond Intelligence.*

2 van Woensel, *Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry.*

3 García-Alvarado, Moroni-Orellana, and Banda-Pérez, *Architectural Evaluation of 3D-Printed Buildings*.

4 Jipa and Dillenburger, *3D Printed Formwork for Concrete.*

5 Ali, Abilgaziyev, and Adair, *4D Printing.*

6 Pegna, *Exploratory Investigation of Solid Freeform Construction.*

7 Tay et al., *3D Printing Trends in Building and Construction Industry.*

8 Perkins and Skitmore, *Three-Dimensional Printing in the Construction Industry.*

9 Khoshnevis and Dutton, *Innovative Rapid Prototyping Process Makes Large Sized, Smooth Surfaced Complex Shapes in a Wide Variety of Materials.*

10 van Woensel, *Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry.*

11 Naboni and Paoletti, *How to Build (Almost) Anything Customized.*

12 Anton et al., *A 3D Concrete Printing Prefabrication Platform for Bespoke Columns.*

13 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone.*

14 Lowke et al., *Particle-Bed 3D Printing in Concrete Construction – Possibilities and Challenges.*



15 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone.*

16 Jipa and Dillenburger, *3D Printed Formwork for Concrete.*

17 van Woensel, *Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry.*

18 García-Alvarado, Moroni-Orellana, and Banda-Pérez, *Architectural Evaluation of 3D-Printed Buildings.*

19 Colla and Pambaguian, *The Design of a Lunar Outpost: 3d Printing Regolith as a Construction Technique For Environmental Shielding on the Moon.*

20 Gardner et al., *Testing and Initial Verification of the World's First Metal 3D Printed Bridge.*

21 Hack et al., *Structural Stay-in-Place Formwork for Robotic in Situ Fabrication of Non-Standard Concrete Structures.*

22 Bos et al., *Additive Manufacturing of Concrete in Construction.*

23 de la Fuente et al., *Structural Fibre-Reinforced Cement-Based Composite Designed for Particle Bed 3D Printing Systems. Case Study Parque de Castilla Footbridge in Madrid.*

24 Salet et al., *Design of a 3D Printed Concrete Bridge by Testing.*

25 *Nijmegen Has the Longest 3D-Printed Concrete Bicycle Bridge in the World.*

26 Xu et al., *Fabrication and Application of 3D-Printed Concrete Structural Components in the Baoshan Pedestrian Bridge Project.*

27 *Striatus 3D Concrete Printed Masonry Bridge.*

28 Burger et al., *Design and Fabrication of a Non-Standard, Structural Concrete Column Using Eggshell: Ultra-Thin, 3D Printed Formwork.*

29 *Free Formwork - Dbt.*

30 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone.*

31 *Dissolvable Formwork - Dbt.*

32 *Additive Archetypes - Dbt.*

33 Anton et al., *A 3D Concrete Printing Prefabrication Platform for Bespoke Columns.*

34 *Krypton, a Column in Aix-En-Provence.*

35 *Design Computation Lab - RC4 - Amalgama.*

36 Bekkering et al., *Architectonic Explorations of the Possibilities of 3D Concrete Printing: The Historic Building Fragment as Inspiration for New Applications with 3D Concrete Printing in Architecture.*

37 *Elements.*

38 Waldschmitt et al., *3d Printing of Column Structures for Architectural Applications.*

39 *Blast Studio. 3D Prints Column from Mycelium.*

40 Vantyghem et al., *3D Printing of a Post-Tensioned Concrete Girder Designed by Topology Optimization.*

41 *3D Printed Reinforced Beam.*

42 De Schutter et al., *Vision of 3D Printing with Concrete — Technical, Economic and Environmental Potentials.*

43 Hansemann et al., *Additive Fabrication of Concrete Elements by Robots: Lightweight Concrete Ceiling.*

44 *3D Printed Slab.*

45 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone.*

46 Graser, Baur, and Norman, *DFAB House: A Comprehensive Demonstrator of Digital Fabrication in Architecture.*

47 *Functional Formwork For a Funicular Floor.*

48 Anton et al., *Fast Complexity.*

49 Peters, *Building Bytes: 3D-Printed Bricks.*

50 *Digital Adobe - IAAC.*

51 Westerlind and Hernández, *Knitting Concrete.*

52 Anton et al., *A 3D Concrete Printing Prefabrication Platform for Bespoke Columns;* Graser, Baur, and Norman, *DFAB House: A Comprehensive Demonstrator of Digital Fabrication in Architecture.*

53 Bekkering et al., *Architectonic Explorations of the Possibilities of 3D Concrete Printing: The Historic Building Fragment as Inspiration for New Applications with 3D Concrete Printing in Architecture.*

54 Burger et al., *Eggshell.*

55 Burger et al.

56 Waldschmitt et al., *3d Printing of Column Structures for Architectural Applications.*

57 *Design Computation Lab - RC4 - Amalgama.*

58 *Free Formwork - Dbt.*

59 *Additive Archetypes - Dbt.*

60 *Dissolvable Formwork - Dbt.*

61 *Krypton, a Column in Aix-En-Provence.*

62 *Krypton, a Column in Aix-En-Provence.*

63 *3D Printed Reinforced Beam.*

64 Anton et al., *Fast Complexity.*

65 Hansemann et al., *Additive Fabrication of Concrete Elements by Robots: Lightweight Concrete Ceiling.*

66 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone,3; 3D Printed Slab.*

67 Graser, Baur, and Norman, *DFAB House: A Comprehensive Demonstrator of Digital Fabrication in Architecture.*

68 *Functional Formwork For a Funicular Floor.*

69 Westerlind and Hernández, *Knitting Concrete.*

70 Peters, *Building Bytes: 3D-Printed Bricks"; Naboni and Paoletti, "How to Build (Almost) Anything Customized.*

71 *Digital Adobe - IAAC.*

## BIBLIOGRAPHY


Ali, Md. Hazrat, Anuar Abilgaziyev, and Desmond Adair. “4D Printing: A Critical Review of Current Developments, and Future Prospects.” *The International Journal of Advanced Manufacturing Technology 105*, no. 1–4 (November 2019): 701–17. https://doi.org/10.1007/s00170-019-04258-0.

Anton, Ana, Andrei Jipa, Lex Reiter, and Benjamin Dillenburger. “Fast Complexity: Additive Manufacturing for Prefabricated Concrete Slabs.” In *Second RILEM International Conference on Concrete and Digital Fabrication*, 28:1067–77. RILEM Bookseries. Cham: Springer International Publishing, 2020. https://doi.org/10.1007/978-3-030-49916-7_102.

Anton, Ana, Lex Reiter, Timothy Wangler, Valens Frangez, Robert J. Flatt, and Benjamin Dillenburger. “A 3D Concrete Printing Prefabrication Platform for Bespoke Columns.” *Automation in Construction 122* (February 2021): 103467. https://doi.org/10.1016/j.autcon.2020.103467.

Bekkering, Juliette, Barbara Kuit, Alessia Biffi, and Zeeshan Yunus Ahmed. “Architectonic Explorations of the Possibilities of 3D Concrete Printing: The Historic Building Fragment as Inspiration for New Applications with 3D Concrete Printing in Architecture.” In *Second RILEM International Conference on Concrete and Digital Fabrication*, 1078–90. Cham: Springer International Publishing, 2020.

Bos, Freek, Rob Wolfs, Zeeshan Ahmed, and Theo Salet. “Additive Manufacturing of Concrete in Construction: Potentials and Challenges of 3D Concrete Printing.” *Virtual and Physical Prototyping 11*, no. 3 (July 2, 2016): 209–25. https://doi.org/10.1080/17452759.2016.1209867.

Burger, Joris, Ena Lloret-Fritschi, Fabio Scotto, Thibault Demoulin, Lukas Gebhard, Jaime Mata-Falcón, Fabio Gramazio, Matthias Kohler, and Robert J. Flatt. “Eggshell: Ultra-Thin Three-Dimensional Printed Formwork for Concrete Structures.” *3D Printing and Additive Manufacturing 7*, no. 2 (April 1, 2020): 48–59. https://doi.org/10.1089/3dp.2019.0197.

Burger, Joris, Ena Lloret-Fritschi, Nizar Taha, Fabio Scotto, Thibault Demoulin, Jaime Mata-Falcón, Fabio Gramazio, Matthias Kohler, and Robert J. Flatt. “Design and Fabrication of a Non-Standard, Structural Concrete Column Using Eggshell: Ultra-Thin, 3D Printed Formwork.” In *Second RILEM International Conference on Concrete and Digital Fabrication*, 1104–15. Cham: Springer International Publishing, 2020.





Carpo, Mario. *The Second Digital Turn: Design Beyond Intelligence*. Writing Architecture. The MIT Press, 2017.

Colla, Valentina, and Laurent Pambaguian. “The Design of a Lunar Outpost: 3d Printing Regolith as a Construction Technique For Environmental Shielding on the Moon.” In *Fabricate 2014. Negotiating Design and Making.* Fabricate. UCL Press, 2014.

dbt.arch.ethz.ch. “Free Formwork - Dbt,” October 4, 2017.

https://dbt.arch.ethz.ch/research-stream/free-formwork/.

De Schutter, Geert, Karel Lesage, Viktor Mechtcherine, Venkatesh Naidu Nerella, Guillaume Habert, and Isolda Agusti-Juan. “Vision of 3D Printing with Concrete — Technical, Economic and Environmental Potentials.” *Cement and Concrete Research 112* (October 2018): 25–36. https://doi.org/10.1016/j.cemconres.2018.06.001.

Design Computation Lab. “Design Computation Lab - RC4 - Amalgama.” Accessed July 8, 2022. https://designcomputationlab.org/rc4-amalgama.

Dezeen. “Blast Studio 3D Prints Column from Mycelium,” January 18, 2022. https://www.dezeen.com/2022/01/18/blast-studio-tree-column-mycelium-design/.

Fuente, A. de la, A. Blanco, E. Galeote, and S. Cavalaro. “Structural Fibre-Reinforced Cement-Based Composite Designed for Particle Bed 3D Printing Systems. Case Study Parque de Castilla Footbridge in Madrid.” *Cement and Concrete Research 157* (July 2022): 106801. https://doi.org/10.1016/j.cemconres.2022.106801.

García-Alvarado, Rodrigo, Ginnia Moroni-Orellana, and Pablo Banda-Pérez. “Architectural Evaluation of 3D-Printed Buildings.” *Buildings 11*, no. 6 (June 15, 2021): 254. https://doi.org/10.3390/buildings11060254.

Gardner, Leroy, Pinelopi Kyvelou, Gordon Herbert, and Craig Buchanan. “Testing and Initial Verification of the World’s First Metal 3D Printed Bridge.” *Journal of Constructional Steel Research 172* (September 2020): 106233. https://doi.org/10.1016/j.jcsr.2020.106233.

Graser, Konrad, Marco Baur, and Hack Norman. “DFAB House: A Comprehensive Demonstrator of Digital Fabrication in Architecture.” In *Fabricate 2020*, 130–39. UCL Press, 2020. https://doi.org/10.2307/j.ctv13xpsvw.

Hack, Norman, Kathrin Dörfler, Alexander Nikolas Walzer, Timothy Wangler, Jaime Mata-Falcón, Nitish Kumar, Jonas Buchli, et al. “Structural Stay-in-Place Formwork for Robotic in Situ Fabrication of Non-Standard Concrete Structures: A Real Scale Architectural Demonstrator.” *Automation in Construction 115* (July 2020): 103197. https://doi.org/10.1016/j.autcon.2020.103197.

HANNAH. “Elements,” December 4, 2022. https://www.hannah-office.org/work/elements.

Hansemann, Georg, Robert Schmidt, Holzinger Christoph, and Joshua Tapley. “Additive Fabrication of Concrete Elements by Robots: Lightweight Concrete Ceiling.” In *Fabricate 2020*, 124–29. UCL Press, 2020. https://www.jstor.org/stable/j.ctv13xpsvw.20.

IAAC. “Digital Adobe - IAAC.” Accessed December 4, 2022.

https://iaac.net/project/digital-adobe/.

Jipa, Andrei, and Benjamin Dillenburger. “3D Printed Formwork for Concrete: State-of-the-Art, Opportunities, Challenges, and Applications.” *3D Printing and Additive Manufacturing 9, no. 2* (April 1, 2022): 84–107. https://doi.org/10.1089/3dp.2021.0024.

Khoshnevis, Behrokh, and Rosanne Dutton. "Innovative Rapid Prototyping Process Makes Large Sized, Smooth Surfaced Complex Shapes in a Wide Variety of Materials." *Materials Technology 13, no. 2* (January 1998): 53–56. https://doi.org/10.1080/10667857.1998.11752766.

Lowke, Dirk, Enrico Dini, Arnaud Perrot, Daniel Weger, Christoph Gehlen, and Benjamin Dillenburger. "Particle-Bed 3D Printing in Concrete Construction – Possibilities and Challenges." *Cement and Concrete Research 112* (October 2018): 50–65. https://doi.org/10.1016/j.cemconres.2018.05.018.

Naboni, Roberto, and Ingrid Paoletti. "How to Build (Almost) Anything Customized." In *Advanced Customization in Architectural Design and Construction*, by Roberto Naboni and Ingrid Paoletti, 77–152. SpringerBriefs in Applied Sciences and Technology. Cham: Springer International Publishing, 2015. https://doi.org/10.1007/978-3-319-04423-1_4.

Nicolas, Ruffray, Bernhard Mathias, Jipa Mihail-Andrei, Aghaei Meibodi Mania, Montague de Taisne Neil, Stutz Felix, Wangler Timothy, Flatt J Robert, and Dillenburger Benjamin. "Complex Architectural Elements from HPFRC and 3D Printed Sandstone." Application/pdf, October 2, 2017, 10 p. https://doi.org/10.3929/ETHZ-B-000237128.

Pegna, Joseph. "Exploratory Investigation of Solid Freeform Construction." *Automation in Construction 5, no. 5* (February 1997): 427–37. https://doi.org/10.1016/S0926-5805(96)00166-5.

Perkins, Isaac, and Martin Skitmore. "Three-Dimensional Printing in the Construction Industry: A Review." I*nternational Journal of Construction Management 15, no. 1* (January 2, 2015): 1–9. https://doi.org/10.1080/15623599.2015.1012136.

Peters, Brian. "Building Bytes: 3D-Printed Bricks," 2013.

Salet, Theo A. M., Zeeshan Y. Ahmed, Freek P. Bos, and Hans L. M. Laagland. "Design of a 3D Printed Concrete Bridge by Testing." V*irtual and Physical Prototyping 13, no. 3* (July 3, 2018): 222–36. https://doi.org/10.1080/17452759.2018.1476064.

Tay, Yi Wei Daniel, Biranchi Panda, Suvash Chandra Paul, Nisar Ahamed Noor Mohamed, Ming Jen Tan, and Kah Fai Leong. "3D Printing Trends in Building and Construction Industry: A Review." *Virtual and Physical Prototyping 12*, no. 3 (July 3, 2017): 261–76. https://doi.org/10.1080/17452759.2017.1326724.

Vantyghem, Gieljan, Wouter De Corte, Emad Shakour, and Oded Amir. "3D Printing of a Post-Tensioned Concrete Girder Designed by Topology Optimization." *Automation in Construction 112* (April 2020): 103084. https://doi.org/10.1016/j.autcon.2020.103084.

Vantyghem, Gieljan, Ticho Ooms, and Wouter De Corte. "VoxelPrint: A Grasshopper plug-in for voxel-based numerical simulation of concrete printing." *Automation in Construction 122* (February 2021): 103469. https://doi.org/10.1016/j.autcon.2020.103469.

Waldschmitt, B., C. Borg Costanzi, U. Knaack, and J. Lange. “3d Printing of Column Structures for Architectural Applications.” *Architecture, Structures and Construction*, May 23, 2022. https://doi.org/10.1007/s44150-022-00050-z.

Westerlind, Helena, and José Hernández. “Knitting Concrete.” In *Second RILEM International Conference on Concrete and Digital Fabrication*, edited by Freek P. Bos, Sandra S. Lucas, Rob J.M. Wolfs, and Theo A.M. Salet, 988–97. Cham: Springer International Publishing, 2020.

Woensel, Remco van. “Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry.” *The International Journal of the Constructed Environment 9, no.* 1 (2018). https://doi.org/10.18848/2154-8587/CGP/v09i01/57-81.

www.dbt.arch.ethz.ch. “3D Printed Reinforced Beam,” November 18, 2017. https://dbt.arch.ethz.ch/project/3d-printed-reinforced-beam/.

www.dbt.arch.ethz.ch. “3D Printed Slab,” February 11, 2018. https://dbt.arch.ethz.ch/project/topology-optimisation-3d-printed-slabs/.

www.dbt.arch.ethz.ch. “Additive Archetypes - Dbt,” November 18, 2019. https://dbt.arch.ethz.ch/project/additive-archetypes/.

www.dbt.arch.ethz.ch. “Dissolvable Formwork - Dbt,” September 27, 2019. https://dbt.arch.ethz.ch/research-stream/dissolvable-formwork/.

www.dbt.arch.ethz.ch. “Functional Formwork For a Funicular Floor,” February 11, 2019. https://dbt.arch.ethz.ch/project/functional-formwork-for-concrete-floors/.

www.striatusbridge.com. “Striatus 3D Concrete Printed Masonry Bridge.” Accessed June 20, 2022. https://www.striatusbridge.com/.

www.tue.nl. “Nijmegen Has the Longest 3D-Printed Concrete Bicycle Bridge in the World,” September 8, 2021. https://www.tue.nl/en/news-and-events/news-overview/01-01-1970-nijmegen-has-the-longest-3d-printed-concrete-bicycle-bridge-in-the-world/#top.

XtreeE. “Krypton, a Column in Aix-En-Provence.” Accessed July 8, 2022. https://xtreee.com/en/project/krypton/.

Xu, Weiguo, Yuan Gao, Chenwei Sun, and Zhi Wang. “Fabrication and Application of 3D-Printed Concrete Structural Components in the Baoshan Pedestrian Bridge Project.” In Fabricate 2020, 140–47. UCL Press, 2020. https://www.jstor.org/stable/j.ctv13xpsvw.22.