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E-mail: *architecturalsciences@gmail.com*

# Three-Dimensional Concrete Printing Technology and Bridge Applications: A Critical Review

Elif Esra BOYLU[1]*

**ORCID 1:** 0000-0002-1899-1995

[1] Doğuş University, Faculty of Art and Design, Department of Architecture, 34775, Istanbul, Türkiye.

** e-mail: eboylu@dogus.edu.tr*

**Abstract**

*This study examines the contributions of three-dimensional (3D) concrete printing technology to architectural practice and evaluates its potential use in bridge construction. Drawing on the existing literature, the advantages and limitations of 3D concrete printing relative to conventional construction methods; particularly in terms of speed, labour requirements, and material efficiency are discussed. Ten bridge structures built with 3D concrete printing between 2017 and 2025 are analysed in terms of equipment, reinforcement strategy, structural span, cross-section geometry, concrete type, and production method. Through paired comparisons of formally and methodologically related bridges, the study traces the year-by-year development of robotic and additive production. The findings highlight the technological advantages, current limitations, and future development opportunities of 3D concrete printing in pedestrian and bicycle bridge infrastructure, offering guidance for integrating this innovative method into architectural technology and education.*

***Keywords:*** *3D Concrete Printing, Bridge Construction, Additive Manufacturing.*

# Üç Boyutlu Beton Yazdırma Teknolojisi ve Köprü Uygulamaları: Eleştirel Değerlendirme

**Öz**

*Bu çalışmada üç boyutlu (3B) beton yazdırma teknolojisinin mimari pratiğe katkıları incelenmekte ve köprü inşasında kullanım potansiyeli değerlendirilmektedir. 3B beton yazdırma; hız, iş gücü gereksinimi ve malzeme verimliliği açısından literatürdeki bulgulara dayanarak avantaj ve sınırlılıkları değerlendirilmiştir. 2017–2025 yılları arasında 3B beton yazdırma ile inşa edilen on köprü yapısı; ekipman, donatı stratejisi, açıklık, kesit geometrisi, beton türü ve üretim yöntemi açısından analiz edilmiştir. Biçimsel ve yöntemsel olarak ilişkili köprülerin eşleştirilmiş karşılaştırmaları yoluyla, robotik ve eklemeli üretimin yıllar içindeki gelişimi izlenmiştir. Elde edilen bulgular, yaya ve bisiklet köprüsü 3B beton yazdırmanın teknolojik avantajlarını, mevcut sınırlılıklarını ve gelecekteki gelişim olanaklarını ortaya koyarak bu yenilikçi yöntemin mimarlık teknolojisi ve eğitimiyle bütünleştirilmesine yönelik yol gösterici değerlendirmeler sunmaktadır.*

***Anahtar Kelimeler:*** *3B Beton Yazdırma, Köprü İnşası, Eklemeli İmalat.*

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## 1. Introduction

Three-dimensional (3D) printing technology is defined as the process of forming an object by depositing material layer by layer (El-Sayegh et al., 2020). Unlike conventional shaping methods—in which material is removed or carved away to obtain the desired form—3D printing builds the object by extruding successive layers through a nozzle until the final geometry is achieved. This fundamental difference is illustrated in Figure 1.

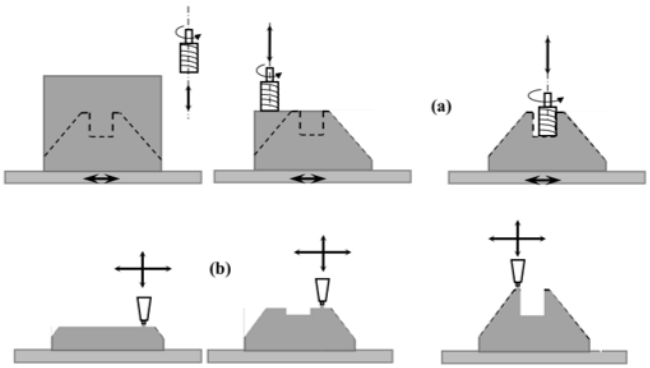



**Figure 1.** Conventional subtractive manufacturing (a) and additive manufacturing through 3D printing (b) (El-Sayegh et al., 2020)

In recent years, 3D concrete printing technology has been tested in a variety of applications, including single-storey buildings, urban furniture, shell structures, and various pavilions. However, the use of this construction system at the structural scale of bridges is still in its early stages (Zhang & Sanjayan, 2025).

Compared with single-storey buildings or pavilions, bridges require considerably higher mechanical performance and durability, since they must safely carry not only their own dead load but also continuously changing live loads. Dynamic loads such as vehicular and pedestrian traffic generate vibration, oscillation, and fatigue effects associated with repeated stresses; therefore, long-term fatigue resistance is a critical part of the design. In addition, because bridges are exposed to continuously varying dynamic effects such as wind loads, seismic movements, and thermal expansion and contraction, they also require special engineering solutions in terms of aerodynamic stability and seismic performance. Owing to open-air exposure, corrosion resistance, waterproofing, regular maintenance, and long service-life planning are also decisive design factors; in pedestrian bridges in particular, the vibration comfort and user safety arising from live loads must additionally be taken into account. When bridges developed and implemented to meet all these structural requirements are examined, the examples across the 2017–2025 spectrum contribute significantly to understanding the development of 3D concrete printing technology over the years. While the bridges built to date serve pedestrian and bicycle traffic, they have not yet been used for vehicular traffic.

3D concrete printing technology offers many significant advantages, including flexibility of on-site or off-site production, more efficient material use compared with conventional construction methods (El-Sayegh et al., 2020; Allouzi et al., 2020; Wang et al., 2020), greater geometric freedom that allows complex designs (Al Jassmi et al., 2018), faster production processes (Jagoda et al., 2020), cost-effective application without the need for formwork (De Schutter et al.,2018), improved sustainability through reduced waste, on-site occupational safety, and a reduction in the required labour force (Bhooshan et al., 2022).

Nevertheless, this technology also has certain limitations: longer production times (García-Alvarado et al., 2021), high overall cost (El-Sayegh et al., 2020; Ahmed et al., 2022), the requirement for specialised printing material such as rheological and stiffening (El-Sayegh et al., 2020; Ahmed et al., 2022; Salet et al., 2018, De Schutter et al.,2018), and the risk of job losses due to the reduced need for workers (El-Sayegh et al., 2020).

The growing interest in 3D-printed bridges has recently been accompanied by review studies that approach the field from different disciplinary perspectives. Zhang & Sanjayan (2025), for instance,

review 3D concrete printing and digital fabrication technologies for bridge construction by classifying them into process categories—extrusion-based, particle-based, and shotcrete-based printing, and digital casting—with an emphasis on concrete-handling and nozzle-based mixing technologies, that is, from a primarily material- and process-engineering standpoint. The present study differs from such category-based reviews in both perspective and method: rather than organising the discussion around printing-process categories, it adopts a project-based, case-oriented approach centred on realised bridges, and evaluates them from the standpoint of architectural design, production strategy, and integration with architectural education. In addition, by comparing formally and methodologically related bridge pairs across successive years, it aims to make the developmental trajectory of the technology explicit—an analytical emphasis that complements, rather than overlaps with, process-oriented engineering reviews.

Within this framework, the aim of this study is to examine ten bridges built with 3D concrete printing technology between 2017 and 2025, to compare them across a consistent set of criteria, and thereby to provide guidance for integrating the technology into architectural practice and education.

### 1.1. Overview of 3D Concrete Printing Technology: The 3D Concrete Printing Process and Equipment

The printing process can be carried out on-site or off-site, and the equipment used in production can vary considerably. As shown in Figure 2, this equipment may include Cartesian systems, cylindrical systems, suspended systems, articulated mechanisms, robotic arms, gantry cranes, and frame-mounted setups.

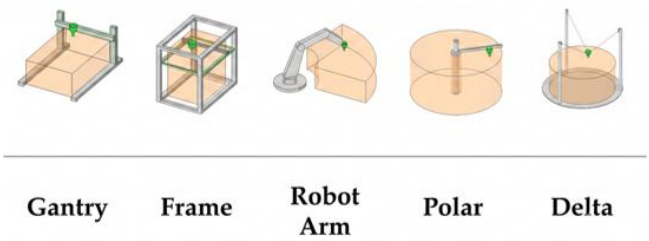



**Figure 2.** Hardware and tools used in printing (Cao et al., 2022)

3D printing technology can be applied through different methods, the most common of which are the following:

- Contour Crafting – A gantry-based system in which a print head guided by CAD data deposits concrete material in successive layers to form the desired geometry (Khoshnevis, 2004) shown in Figure 3 (left).
- Concrete Printing – Similar to contour crafting, but generally using high-performance concrete; the material is extruded layer by layer through a nozzle (El-Sayegh et al., 2020) shown in Figure 3 (right).

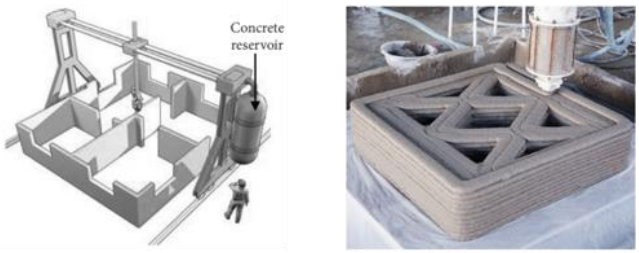



**Figure 3.** Contour crafting (left) and the concrete printing process (right) (Allouzi et al., 2020); concrete printing of a Tsinghua Bridge element (Xu et al., 2020)

- Selective Binder (Cement) Activation (SPI, SCA) – Layers in a powder bed are selectively solidified using a liquid binder to obtain a three-dimensional object (Lowke et al. 2018). The unused powder can be reused, while the printed component is cleaned and removed from the system (Talke et al., 2019) shown in Figure 4(left).
- Binder Jetting –This process originated in metal manufacturing and produces a solid form by selectively jetting a bonding agent over a bed of powder or sand, layer upon layer (García-Alvarado

et al., 2021). Is best known construction-scale version D-Shape, was created by Enrico Dini and can reach build dimentions of 6 × 6 × 6 m (Al Jassmi et al., 2018) shown in Figure 4(middle).

- Shotcrete 3D Printing – This method derives from wet-mix sprayed concrete. The structural element is built up as compressed air drives succesive layers of fine-grained concrete or cement mortar through the nozzle (Rennen et al., 2023) shown in Figure 4(right).



**Figure 4.** Post-printing cleaning in selective cement activation, printing with Binder Jetting (D-Shape), and production with the shotcrete spraying technique (Talke et al., 2019; Jakupović, 2016; Rennen et al., 2023).

## 2. Material and Method

This study is a critical review based on the examination of bridge structures produced with 3D concrete printing technology. Within the scope of this study, all bridge structures produced using 3D concrete printing technology since the emergence of the method were identified and examined. A literature and project-report search was conducted covering the period from 2017—the year in which the first 3D-printed bridge was realised—to 2025. The search was carried out using keywords such as "3D printed bridge," "3D concrete printing bridge," "additive manufacturing bridge," and "robotic concrete printing bridge" in academic databases (e.g., Scopus, Web of Science, Google Scholar) as well as official project reports and institutional publications. All identified structures satisfying the following criteria were included:

- the structure is a bridge (serving pedestrian, bicycle, or vehicular traffic) rather than a building, pavilion, or other typology;
- the primary load-bearing elements were produced through 3D concrete/mortar printing; and
- sufficient technical documentation—such as a peer-reviewed publication, official project report, or detailed conference paper—was available regarding the production method, materials, and structural dimensions.

As a result of this process, ten bridges built between 2017 and 2025 were identified as constituting the complete set of documented 3D-printed concrete bridges to date, and were included in this study. This comprehensive scope allows the developmental trajectory of the technology to be traced without the risk of selective omission.Each bridge was analysed on the basis of project reports and peer-reviewed publications in terms of four main axes:

1. the production method and equipment used,
2. cross-section geometry, reinforcement condition, and number of unit elements,
3. concrete type and strength, and
4. location, span, and function.

The data obtained were organised into comparative tables, and bridges that are formally and methodologically related were further evaluated through paired comparisons in order to trace the development of the method over time.

## 3. Findings and Discussion

### 3.1. Technical Insights from previous studies on Reinforcement and Cross-Section Strategies

In a study on 3D printing (Cao et al., 2022), it was reported that the robotic arm remains the most widely used system among different printing methods. However, the same study emphasised that delta and circular systems have higher setup costs, whereas frame and gantry systems are more widely

preferred owing to their lower costs, easy installation, and simple maintenance requirements. Building on these technological differences, Figure 5 presents various wall-printing patterns and their reinforced versions. Furthermore, studies on extrusion-based printing have focused on overcoming interlayer weakness by integrating continuous reinforcement during the deposition process. Research has demonstrated that utilizing a custom-designed nozzle to simultaneously embed steel reinforcing mesh into the extruded concrete filament effectively provides structural continuity across layers and significantly enhances flexural performance (Marchment & Sanjayan, 2020).

The study showed that adding reinforcement increases structural strength but lengthens the production time compared with unreinforced printing. The main filament-deposition patterns observed in practice are the simple layout, the parallel-lattice layout, the filled parallel layout, and the hollow parallel layout; these walls can further be strengthened with horizontal, vertical, or densified bar-reinforcement configurations (García-Alvarado et al., 2021).

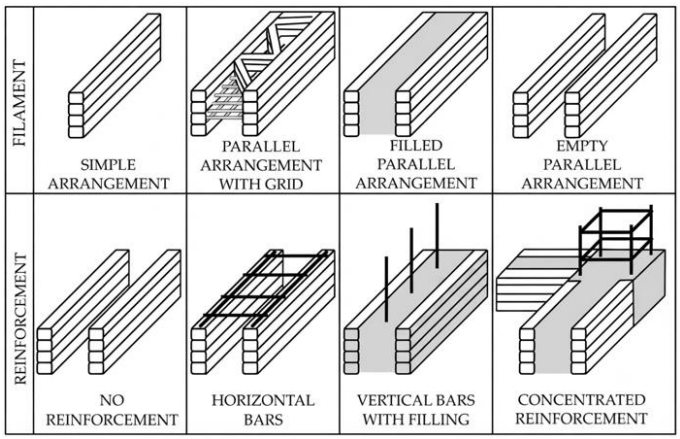



**Figure 5.** Wall types produced through 3D printing and the reinforcement methods of these walls (García-Alvarado et al., 2021)

In addition, the hollow-section design approach, which aims to increase material efficiency, allows structurally safe production even without the use of reinforcement. Figure 6 shows the different hollow sections that can be applied to achieve this effect. Unlike conventional construction methods, 3D concrete printing deposits only the required amount of material, and when combined with hollow-section strategies it offers significant material savings in terms of both structural efficiency and weight reduction (Wang et al., 2020).

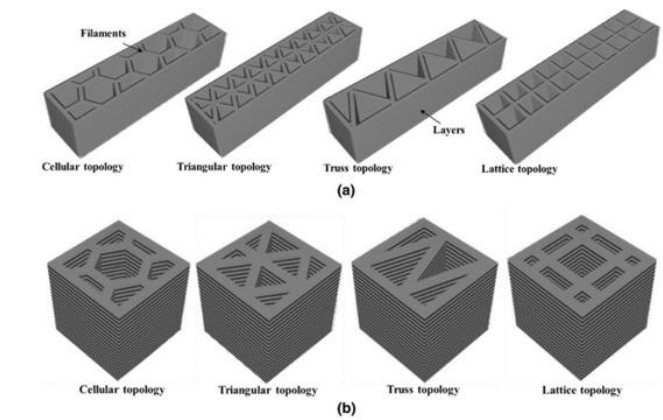



**Figure 6**. Hollow cross-section forms (Adapted from Wang et al., 2020)

### 3.2. Case Analysis of 3D-Printed Bridges

In this section, the ten bridges produced with 3D concrete printing technology and examined in this study are introduced. Table 1 presents an overview of these bridges, summarising their location, year of construction, function, total length, and maximum span. As shown in the table, the bridges span a

construction period from 2017 to 2024 and range considerably in scale, from 4 m research prototypes to full-scale structures exceeding 20 m in length.

**Table 1.** Summary of bridge location, year, function, length, and span data (Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Dell'Endice et al., 2024; Rennen et al., 2023)

| Bridge | Location | Year | Function | Bridge Lenght | Max.Span |
|---|---|---|---|---|---|
| **IAAC** Bridge | Madrid, Spain | 2017 | Pedestrian | 12 m | 12 m |
| Gemert Bridge | The Netherlands | 2017 | Pedestrian + bicycle | 8 m | 6.5 m |
| Vertico Bridge | Belgium | 2020 | Pedestrian | 4 m | 4 m |
| Baoshan (Tsinghua) Bridge | Shanghai, China | 2019 | Pedestrian | 23.6 m | 14.4 m |
| Striatus Bridge | Venice, Italy | 2021 | Pedestrian + bicycle | 16.6 m | 16.6 m |
| Xiang Phoenix Bridge | Shanghai, China | 2021 | Pedestrian | 9.5 m | 6 m |
| Nijmegen Bridge | The Netherlands | 2021 | Pedestrian + bicycle | 29 m | 6.5 m |
| Phoenix Bridge | Lyon, France | 2023 | Pedestrian + bicycle | 18 m | 16 m |
| Knitcrete & Shotcrete Bridge | Germany | 2023 | Pedestrian | 4.5 m | 4 m |
| External-cable reinforced bridge | China – Australia | 2024 | Pedestrian | 4 m | 4 m |

Each example is presented with a detailed description of its technical characteristics and construction process. Key data such as the year of construction, structural dimensions, production method, material properties, and assembly process are provided in order to establish a clear and descriptive basis for the subsequent comparative analysis.

### 3.2.1. IAAC 3D-Printed Bridge / Madrid, Spain / 2017

According to the report of the Institute for Advanced Architecture of Catalonia, this bridge is the first application of 3D printing technology in the field of civil engineering. The bridge is 12 m long and 1.75 m wide (Pons-Valladares et al., 2023) shown in Figure 7.



**Figure 7.** IAAC pedestrian bridge, Madrid (Adapted from IAAC, 2017)

Built using micro-reinforced concrete, the structure minimises both material use and waste while maintaining structural performance. The project was implemented in Alcobendas Park in the Castilla-La Mancha region of Madrid, Spain. With its parametric design, the bridge was produced using the D-Shape robotic concrete printing process. Production took 45 days, and the bridge consists of eight U-shaped segments (Figure 8), each cast in a production chamber with steel-reinforced mortar and cured with the aid of heat.

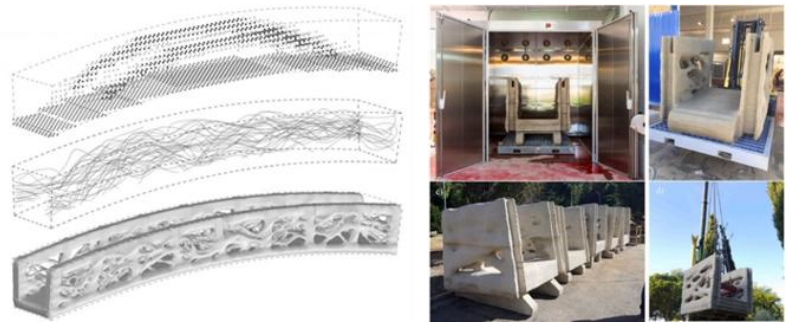


**Figure 8** Design development image; (right) curing device and unit components (Pons-Valladares et al., 2023)

Temporary steel girders were used during construction to support assembly (Pons-Valladares et al., 2023). Figure 9 shows the temporary steel support system and the form of the bridge composed of eight parts. Each bridge part measures 2 × 2 × 2 m (Pons-Valladares et al., 2023); this size limitation was determined in order to obtain the highest efficiency from the method used.




**Figure 9.** Segmented bridge structure and the temporary steel supports below (Pons-Valladares et al., 2023)

### 3.2.2. Gemert Bicycle and Pedestrian Bridge / The Netherlands / 2017

This bicycle and pedestrian bridge, located in the village of Gemert in the Netherlands, crosses a small canal (Figure 10) according to the project report (Salet et al., 2018). It is 6.5 m long and 3.5 m wide. Each structural unit was produced with a gantry-type 3D printer and, after printing, was rotated 90 degrees and assembled through the combination of pre-tensioned and post-tensioned tendons (Figure 11) (Salet et al., 2018).



**Figure 10** Gemert bicycle and pedestrian bridge, The Netherlands (Salet et al., 2018)

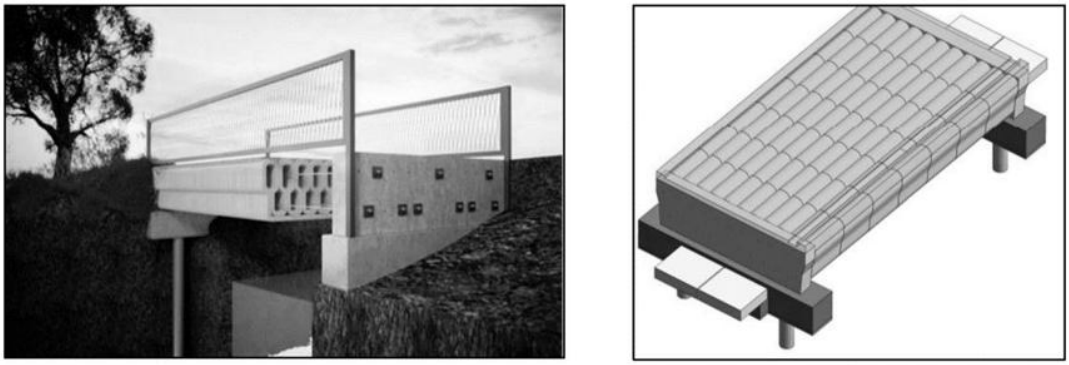


**Figure 11** (Right) bridge tensioning elements and (left) the model of the bridge structure composed of seven parts (Salet et al., 2018)

Weber Print Mortar was used as the printing material. The bridge consists of hollow-section elements (Figure 12) through which the tendons are passed and tensioned. Each unit is 3.44 m wide and 0.92 m high; the total printing time of all components was 48 hours (Salet et al., 2018). This project is recognised as the world's first 3D-printed bridge built with pre-tensioned elements using Fused Deposition Modeling (FDM) technology (Salet et al., 2018).



**Figure 12** (Left) element printing with a gantry crane; (right) printing with reinforcement added in a hollow-section structure (Salet et al., 2018)

### 3.2.3. Tsinghua University 3D-Printed Bridge / Shanghai, China / 2019

Built as a pedestrian bridge in Shanghai, China, in 2019, the Tsinghua University 3D-Printed Bridge (Figure 13) held the record at the time of its completion for the longest span composed entirely of 3D-printed segments. In this full-scale 3D concrete printing project, several critical factors had to be considered beyond determining the ratios of cement, sand, fibre, and water. Because the structure was produced with a 3D robotic printing arm, the extrudability of the concrete mixture was particularly important. While water-reducing admixtures increased the fluidity of the mixture, the use of thinning agents was also necessary to maintain the correct viscosity.



**Figure 13.** Tsinghua pedestrian bridge (Xu et al., 2020)

The bridge consists of 44 three-dimensionally printed concrete segments. The railings comprise 68 printed components, and the deck is made up of 64 patterned panels (Xu et al., 2020). With a total length of 23.6 m and a span of 14.4 m (Figure 14), the structural design of the bridge was inspired by the historic Anji Bridge.

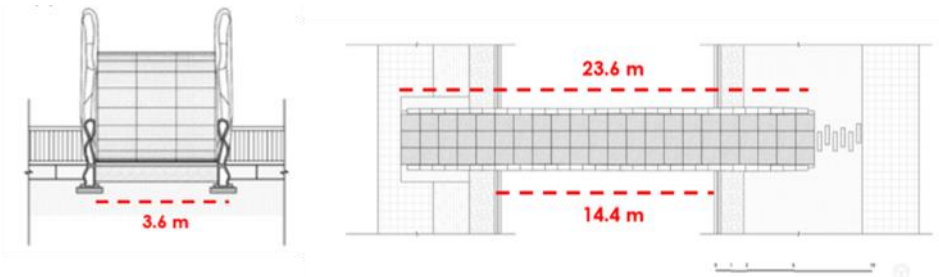



**Figure 14.** Tsinghua Baoshan pedestrian bridge cross-section and plan dimensions (Xu et al., 2020)

Two robotic printing arms were used in the production process; the 44 segments forming the main body were produced in 200 hours, and the patterned deck and railing components in 250 hours, so that the entire structure was completed in a total of 450 hours. Polyethylene-fibre-reinforced composite concrete was used as the material (Xu et al., 2020). Each element, measuring 90 × 90 cm, was placed in sequence on five temporary steel support arches (Figure 16) (Xu et al., 2020). Neither reinforcement nor formwork was used in production (Figure 15). Examination of the printed elements shows that their cross-sections consist of a special hollow geometry, which both increases structural strength and allows the bridge to be built without the need for reinforcement. According to the producers, this method reduced the total manufacturing time by approximately one-third compared with conventional bridge construction and also provided cost savings (Xu et al., 2020).



**Figure 15.** (Left) hollow-section structure of the bridge unit elements; (right) printing of the bridge railings with a robotic arm (Xu et al., 2020)



**Figure 16.** Tsinghua pedestrian bridge, image from the application: steel support girders and concrete parts (Xu et al., 2020).

### 3.2.4. Ghent University – Vertico Pedestrian Bridge / Ghent, Belgium / 2020

Topology optimisation is a method used to optimise the placement of materials within a given design space according to design constraints (Vantyghem et al., 2020).In this bridge study, ultra-high-performance concrete and post-tensioning tendons were used to create an efficient design. The bridge consists of 18 symmetrical parts, 9 on the right and 9 on the left (Figure 17); each part has a maximum total weight of 30 kg and a height not exceeding 40 cm (Vantyghem et al., 2020). After the parts are printed and a 14-day hardening period is observed, a tensioning process is applied with a special mould (Figure 18).



**Figure 17.** (Left) Image of the girder-bridge structure (Vantyghem et al., 2020) (right-up)bridge tendon and reinforcement placement; (right-down)the segmented structure of the bridge (Vantyghem et al., 2020)



**Figure 18** (Left) printed parts, (centre) insertion of reinforcement, (right) injection application (Vantyghem et al., 2020)

The girder spans 4 m (Vantyghem et al., 2020). The researchers state that, after accounting for live loads and the self-weight of the girder, the total material saving achieved with this method was 20%. The study demonstrates that, in addition to formwork-free production of complex geometry, robotic production through 3D printing is feasible (Vantyghem et al., 2020).

### 3.2.5. Striatus, Unreinforced 3D-Printed Bridge / Venice, Italy / 2021

Built in 2021 using 3D concrete printing technology, the Striatus Bridge (Figure 19) is an unreinforced arch-form pedestrian bridge designed to be demountable and reusable. Developed as a full-scale field application, the project was realised through the collaboration of Zaha Hadid Architects and ETH Zurich. All components were engineered to work in compression only, making it possible to build the bridge without any need for reinforcement or tensile elements (Dell'Endice et al., 2023). This design strategy enabled maximum efficiency with minimum material and allowed the structure to be dismantled and relocated, or individual blocks to be repaired, when required (Dell'Endice et al., 2023).



**Figure 19.** View of the Striatus Bridge (Dell'Endice et al., 2023)

The bridge has a 16 m span and consists of a total of 53 printed blocks; all blocks were produced within a printing time of 84 hours. According to the project report, the total weight of the blocks is approximately 24.5 tonnes (Bhooshan et al., 2022). The orthographic representations of the bridge are shown in Figure 20. A spider crane and a five-person team were used for on-site assembly; including a two-week logistical delay (Figure 21), the installation and construction process was completed in 35 days. All joints were applied using the dry-connection method (Bhooshan et al., 2022).

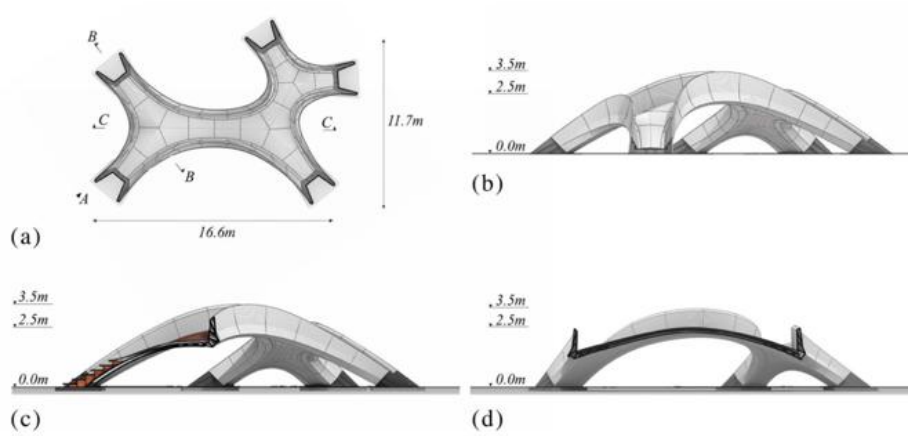



**Figure 20.** Striatus Bridge, plan, section, and elevation (Bhooshan et al., 2022)

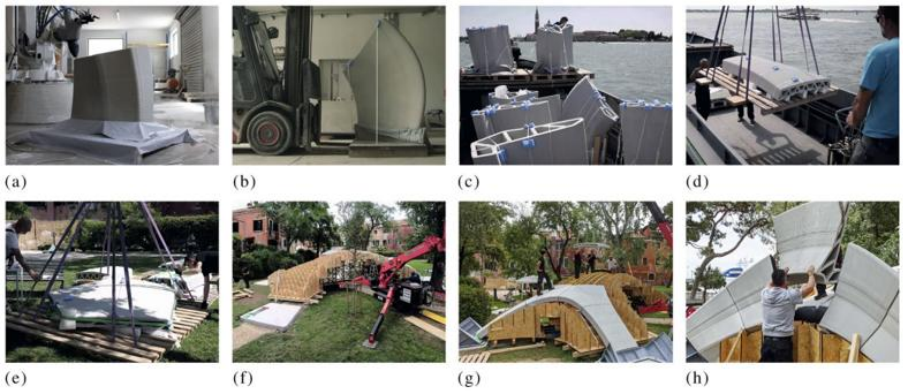



**Figure 21.** Image of bridge production from part manufacturing in the factory to on-site application (Bhooshan et al., 2022)

### 3.2.6. Nijmegen Bicycle and Pedestrian Bridge / The Netherlands / 2021

Built in Nijmegen, the Netherlands, in 2021, this bridge (Figure 22) holds the title of the longest-span bridge produced with 3D concrete printing technology. The project was carried out in collaboration with TU Eindhoven, and its design was made by Michael van der Kley. The structure consists of five superstructure girders and eight columns (Figure 23), with four pairs of columns anchored to pile foundations (Ahmed et al., 2022).



**Figure 22.** Completed bridge image (Adapted from Eindhoven University of Technology, 2021)



**Figure 23.** Images during application: the body anchored with abutments at the start, pre-tensioned elements in the middle, and the bridge view at the end (Ahmed et al., 2022)

After production was completed, both the columns and the bridge segments were rotated 180 degrees before assembly. Filler material was used during the printing process to achieve the outward-curved geometry of the columns; after the first printing attempt failed (Figure 24), the column geometry was revised (Ahmed et al., 2022).



**Figure 24.** Printing of the column elements: (left) the first column design, (right) the updated version (Ahmed et al., 2022)

After printing, the girder elements were covered with plastic sheets to ensure proper curing. The thin components of each girder, visible as cross-sections in the second photograph of Figure 25, were bonded to one another with a synthetic epoxy-based resin. To connect the six girder segments, anchor blocks made of cast-in-place concrete were placed at the front and rear of each part (Ahmed et al., 2022).

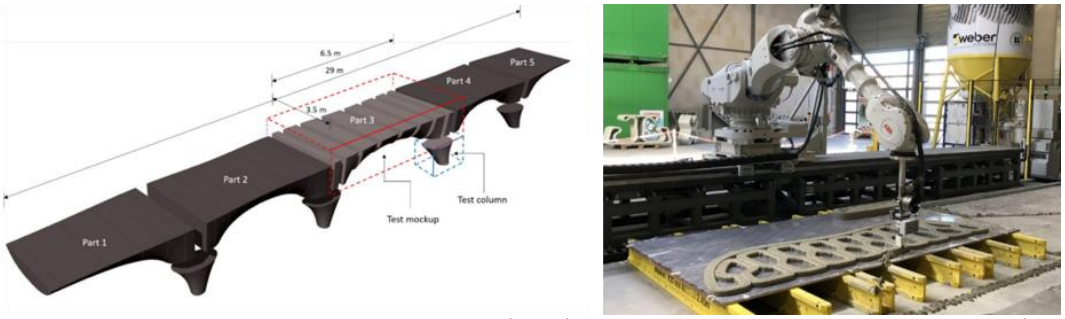



**Figure 25.** Bridge part distribution and dimensions; (right) the robotic arm printing the girder parts (Ahmed et al., 2022)

This experimental project, carried out in a university partnership, investigated the feasibility of the robotic production method for long-span, large-scale applications. The researchers verified the structural safety and practical applicability of the method; however, they also noted that, in its current form, it is not yet ideal in terms of material efficiency and cost (Ahmed et al., 2022).

### 3.2.7. Xiang Phoenix 3D Box Bridge / Shanghai, China / 2021

Built in 2021 as a pedestrian landscape bridge (Figure 26) in the Xi'ang district of Shanghai, this two-hinged arch bridge was constructed using a masonry technique. With a width of 2 m, the bridge has a total length of 9.5 m and spans 6 m (Yang et al., 2024). The parts were 3D-printed off-site using a robotic arm and the polypropylene-modified concrete layer-printing method (Yang et al., 2024). It consists of a total of 53 blocks in four categories (Figure 27-right), with dimensions ranging from 59 to 69.5 cm and from 35.3 to 55.7 cm, and a thickness of 11.5 cm (Yang et al., 2024). For aesthetic effect, 40 'wave-shaped wing' railing parts (Figure 27-left) were also concrete-printed and produced off-site (Yang et al., 2024).



**Figure 26.** (Left) conceptual design image, (right) the produced bridge structure, taken from the article (Yang et al., 2024)

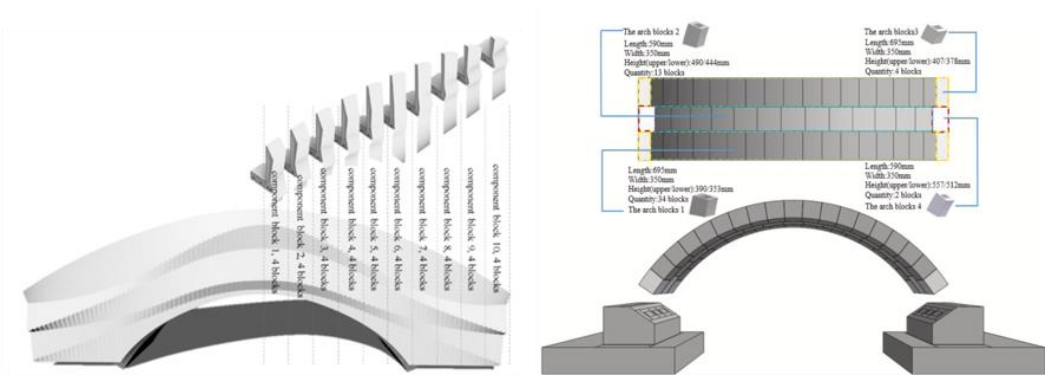


**Figure 27.** (Left) distribution of the 10 different parts for the 3D-printed railing; (right) distribution of the boxes forming the ring-shaped arch, taken from the article (Yang et al., 2024)

The concrete parts (Figure 28) were first exposed to moisture for 24 hours for initial curing, then standard-cured for 28 days (Yang et al., 2024). On-site installation took approximately 3 days (Yang et al., 2024). No information is available on the total printing time of the elements by the robotic arm.



**Figure 28.** (Top) concrete box parts of the arch ring, (bottom) concrete-printed railing element, (side) the robotic arm used in concrete printing (Yang et al., 2024).

As a proof-of-concept engineering demonstration project, this bridge tested the applicability of large-scale 3D concrete printing with a robotic arm in a real, complex, load-bearing structure, while demonstrating the producibility of a long-span bridge that does not require conventional formwork or scaffolding. With an installation time as short as 3 days, it also demonstrates engineering validity and material efficiency in the field (Yang et al., 2024).

### 3.2.8. Phoenix Bridge – Lyon, France / 2023

The Phoenix Bridge (Figure 29), also referred to as Striatus 2.0, was produced in France as a pedestrian and bicycle bridge as an improved and developed version of the bridge built in 2021. Lessons learned from the previously built bridge were taken into account in the new design. The new design has a shallower arch form and a greater number of blocks, and the height of the railing blocks was reduced. The main reason for this is that the size of the blocks in the 2021 design caused difficulties in portability and manoeuvring during assembly.



**Figure 29.** Image of the Phoenix Bridge (Dell'Endice et al., 2024)

The design consists of a total of 75 printed concrete parts (Figure 30), produced in 67 hours (Dell'Endice et al., 2024). The clear span of the arch is 16 m and the total length of the bridge is 18 m (Dell'Endice et al., 2024).



**Figure 30.** (Left) one of the concrete elements printed through layer printing; (right) bridge assembly and the scaffolding structure (Dell'Endice et al., 2024)

Assembly was completed with the aid of temporary scaffolding, and neoprene pads were used to reduce stresses between the blocks (Dell'Endice et al., 2024). A concrete printing mortar called Tector Print was used for this project; unlike the Striatus bridge, no fibre admixtures were used (Dell'Endice et al., 2024).

### 3.2.9. Robotic Knitcrete: 3D Shotcrete-Printed Pedestrian Bridge / 2023

The project is a pedestrian bridge prototype (Figure 31) realised at the Digital Building Fabrication Laboratory (DBFL) of TU Braunschweig in Germany. The main objective of this study was stated to be the development of an additive, design-based production process as an alternative to conventional formwork and conventional production methods, by combining 3D-knitted formwork technology (Figure 32) and robotic shotcrete 3D-printing technology. Unlike the other examples, the bridge structure was produced as a single-piece shell structure. With dimensions of 4.5 m in length and 1.6 m in width, the bridge prototype spans 4 m (Rennen et al., 2023).

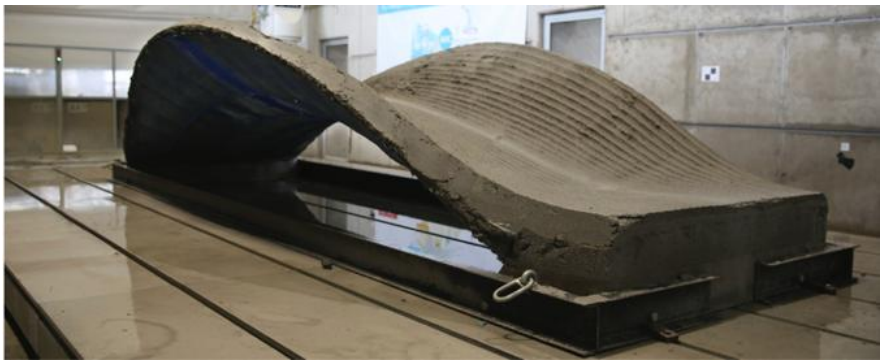


**Figure 31.** Finished state of the bridge produced with the shotcrete 3D-spraying method (Rennen et al., 2023)



**Figure 32.** (Left) the knitcrete formwork structure of the bridge; (right) the concrete-spraying process (Rennen et al., 2023)

In its construction, a Portland-cement-based cement grout without fine aggregate and a (micro-polypropylene) polymer-reinforced, cement-based, fine-grained concrete (Nafufill KM 250) were used (Rennen et al., 2023). The production of the knitted formwork took 4 hours (Rennen et al., 2023). The

robotic fibre winding required approximately 110 minutes, and 24 hours of curing time was required for the epoxy. It was applied with 15 spraying passes. A six-axis robotic arm was used (Rennen et al., 2023).

### 3.2.10. Flat Concrete Bridge Reinforced with External Cables / 2024

This study is a pedestrian bridge prototype carried out through the collaboration of Tongji University (Shanghai, China) and RMIT University (Melbourne, Australia). Multi-material topology optimisation was applied. Composed of 9 printed concrete elements working in compression and 2 parallel steel cables working in tension, the bridge structure (Figure 33) has an internally unreinforced, demountable, and re-assemblable form (Li et al., 2024).



**Figure 33.** Conceptual image of the bridge (Li et al., 2024)

The parts have a hollow cross-section. With a width of 60 cm and a span of 4 m, the bridge structure was printed using a six-axis industrial robotic arm (Li et al., 2024). The parts (Figure 34) were produced off-site and joined on-site using the dry-assembly method. A high-strength (50 MPa), fine-aggregate concrete suitable for 3D printing was used as the concrete type (Li et al., 2024).



**Figure 34.** (Top) bridge parts and (bottom) the assembled bridge structure (Li et al., 2024)

### 3.3 Comparative Summary of Production Methods, Cross Sections, and Materials

Having examined each bridge individually, this section presents a comparative summary of the production methods, cross-section strategies, and material properties across all ten cases, based on Tables 2, 3, and 4. Table 2 summarises the printing method, equipment, and production time for each bridge.

Among the structures listed in Table 2, in which the method, equipment, and durations used are specified, the Vertico and Nijmegen bridges were left to reach a certain hardness while the printed parts were removed from the printer, because sand was used as filler during printing. The fastest production among them was achieved in the Gemert bridge in the Netherlands. When the Striatus and Phoenix bridges are compared, it is seen that the printing time decreased in the Phoenix bridge.

**Table 2.** Summary of the 3D printing methods, equipment used, and production time of the bridges (Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Dell'Endice et al., 2024; Rennen et al., 2023; Li et al., 2024)

| Bridge | Method used | Equipment used | Printing time |
|---|---|---|---|
| IAAC Bridge | D-Shape | D-Shape | 45 days |
| Gemert Bridge | 3D printing | Gantry crane | 48 hours |
| Vertico Bridge | 3D printing | Robotic arm | n/a – 14-day strength period |
| Baoshan Bridge | 3D printing | Robotic arm | 250 + 200 hours (≈19 days) |
| Striatus Bridge | 3D printing | Robotic arm | 84 hours + 35 days |
| Nijmegen Bridge | 3D printing | Robotic arm | n/a – 48 h de-moulding time |
| Xiang Phoenix Bridge | 3D printing | Robotic arm | n/a, 3 days installation |
| Phoenix Bridge | 3D printing | Robotic arm | 67 hours |
| Knitcrete & Shotcrete Bridge | Shotcrete spraying | Robotic arm | n/a |
| External-cable reinforced bridge | 3D printing | Robotic arm | n/a |

Sand is used in parametrically formed structures in order to preserve the form during printing. When the printing time is considered, three-dimensional printing technology is seen to be fast compared with conventional production. Among the printed bridges, the three-dimensional printing method was mostly used among additive production methods, and the robotic arm was largely chosen as equipment.

As summarized in Table 3, the examined bridge structures exhibit significant variations in terms of unit element cross-sections, reinforcement strategies, printing infill conditions, and the total number of constituent blocks. While hollow and box-like cross-sections are predominantly preferred to optimize material efficiency and structural weight, several complex geometries rely on specialized internal layouts or external support strategies during the printing process. Furthermore, the variation in unit element counts; ranging from monolithic shell applications to multi-segment masonry and post-tensioned assemblies, highlights how different structural systems address the scalability and constructability challenges of 3D concrete printing at the pedestrian- and bicycle-bridge scale.

**Table 3.** Summary of the cross-section forms, reinforcement conditions, and number of unit elements of the bridges (Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Dell'Endice et al., 2024; Rennen et al., 2023; Li et al., 2024).

| Bridge name | Unit element section | Reinforced / unreinforced | Printing: filled / unfilled | Unit count (body) |
|---|---|---|---|---|
| IAAC Bridge | Solid section | Unreinforced | Printed into filler | 8 |
| Gemert Bridge | Hollow section | Reinforced – pre/post-tension | Unfilled | 7 |
| Vertico Bridge | Hollow section | Reinforced – tendon | Sand-filled | 18 |
| Baoshan Bridge | Hollow section | Unreinforced | Unfilled | 44 |
| Striatus Bridge | Hollow section | Unreinforced | Unfilled | 53 |

| | | | | |
|---|---|---|---|---|
| Nijmegen Bridge | Hollow section | Reinforced – pre/post-tension | Sand-filled | 44 (36+8) |
| Xiang Phoenix Bridge | Box section | Unreinforced | Unfilled | 53 |
| Phoenix Bridge | Hollow section | Unreinforced | Unfilled | 75 |
| Knitcrete & Shotcrete Bridge | Sprayed solid | Knitcrete mesh | Unfilled | 1 (single piece) |
| External-cable reinforced bridge | Hollow section | Reinforced / external | Unfilled | 9 |

Table 4 lists the type of concrete used and its compressive strength. In the listed bridge structures, it is seen that strength increases on a year basis, and that admixed and ultra-high-performance concrete are used (Miri et al. 2025). Concrete is inherently strong in compression and weak in tension. In 3D-printed concrete elements, tensile stress is the weakest limit of the material, and when this limit is exceeded, the probability of micro-cracks, inter-layer separations, and consequently macro-cracks and fractures increases (Yang et al., 2024). For this reason, during the design stage, geometry, strengths, and support conditions (such as reinforcement and tendons) are configured so as not to approach the laboratory-measured tensile strength (Li et al., 2024; Salet et al., 2018). Before field application, checks are carried out to prevent unexpected tensile stresses (Dell'Endice et al., 2024). Confirming this information, the examination of the bridges shows that the hollow-section, unreinforced elements have a particular cross-section geometry, and that pre- and post-tensioning elements were used in some examples.

**Table 4.** Summary of the concrete type and strength data used in the bridge productions (Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Dell'Endice et al., 2023; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Rennen et al., 2023; Li et al., 2024).

| Bridge | Concrete type used | 28-day compressive strength | Tensile strength |
|---|---|---|---|
| IAAC Bridge | Steel-reinforced mortar | < 25 MPa | n/a |
| Gemert Bridge | Weber Print Mortar | 22 MPa | 1.3 MPa |
| Vertico Bridge | UHPC (ultra-high-performance concrete) | 80 MPa | 1 MPa |
| Baoshan Bridge | Polyethylene-fibre concrete | 70–75 MPa | 1.5–2 MPa |
| Striatus Bridge | Fibre-reinforced concrete mix | 75–80 MPa | 3.5 MPa |
| Nijmegen Bridge | Weber Print Mortar (Weber 3D 145-2) | 30 MPa | 1–2 MPa |
| Xiang Phoenix Bridge | Polypropylene-modified concrete | 60 MPa | 4–5 MPa |
| Phoenix Bridge | Tector Print Mortar | 50 MPa | 1.52 MPa |
| Knitcrete & Shotcrete Bridge | Micro-PP-reinforced fine concrete (Nafufill KM 250) | n/a | n/a |
| External-cable reinforced bridge | Fine-aggregate concrete for 3D printing | 50 MPa | n/a |

Among the ten bridges examined, only the Vertico–external-cable-reinforced pair and the Striatus–Phoenix pair exhibit sufficient formal and methodological continuity—namely, a shared or closely related design team, comparable structural typology, and an explicitly documented design evolution—to allow a meaningful paired comparison. The remaining six bridges, while informative individually, do not share such a direct developmental relationship with one another; their critical strengths and limitations are instead summarised collectively in Table 5.

**Table 5.** Critical summary of key advantages and limitations of the ten examined 3D-printed concrete bridges(Pons-Valladares et al., 2023; Salet et al., 2018; Vantyghem et al., 2020; Xu et al., 2020; Dell'Endice et al., 2023; Bhooshan et al., 2022; Yang et al., 2024; Ahmed et al., 2022; Rennen et al., 2023; Li et al., 2024).

| Bridge | Key Advantages | Key Limitations |
|---|---|---|
| IAAC Bridge | First proof-of-concept application of 3D printing in civil engineering; complex parametric ornamentation achieved without formwork | Long production time (45 days); required temporary steel girders for assembly; small unit size (2×2×2 m) limited scale |
| Gemert Bridge | First pre-tensioned bridge produced via FDM; fast printing time (48 hours) | Reliance on post-printing tensioning process adds construction complexity; hollow units required precise tendon alignment |
| Vertico Bridge | Demonstrated feasibility of topology-optimised, post-tensioned robotic printing; 20% material saving | Small scale (4 m span) limits direct applicability to full-size infrastructure; 14-day hardening period before tensioning |
| Baoshan Bridge | Longest span at the time; formwork- and reinforcement-free hollow geometry; ~1/3 reduction in manufacturing time versus conventional methods | Long total process time (~450 hours including deck/railing); required five temporary steel support arches |
| Striatus Bridge | Fully unreinforced, compression-only design; demountable and repairable | Long installation time (35 days incl. logistics); steep arch reduced accessibility (required steps) |
| Nijmegen Bridge | Longest-span 3D-printed bridge to date (29 m); validated large-scale robotic feasibility | Column geometry failed on first attempt and required redesign; not yet cost- or material-efficient in its current form |
| Xiang Phoenix Bridge | Fast on-site installation (3 days); validated long-span masonry-type arch without scaffolding | No data available on total printing time, limiting comparability; material efficiency not yet optimal |
| Phoenix Bridge | Improved version of Striatus; reduced installation time (3 days vs. 35); smaller, more manoeuvrable blocks | Flatter arch reduced clear height beneath the bridge, limiting passage |
| Knitcrete & Shotcrete Bridge | Novel single-piece shell structure combining knitted formwork and shotcrete printing; formwork-free complex geometry | Limited to small-scale prototype (4 m span); no data on cost or scalability |
| External-cable reinforced bridge | Reduced material strength requirement (50 MPa) via external tensioning; demountable and reassemblable, improving sustainability | Small scale (4 m span); reliance on external steel cables partially offsets the "unreinforced" printing advantage |

### 3.4. Comparative Evaluation of Methodologically Related Bridges

Among the examined examples, the Vertico post-tensioned girder bridge produced in 2020 and the external-cable reinforced bridge produced in 2024 carry formal and methodological similarities, and therefore offer the potential for a comparative evaluation of the development of robotic production. Both bridge structures (Figure 35) were produced as research prototypes.



**Figure 35.** (Left) the 2020 Vertico post-tensioned girder (Vantyghem et al., 2020) and (right) the 2024 external-cable reinforced bridge (Li et al., 2024).

Tensioning elements were used in both bridges. The main difference in the bridge built in 2024 is that the external-cable reinforced bridge was configured to be dismantled and rebuilt, with the cables able to be integrated into the system during installation. This provides an advantage in terms of carbon emissions and sustainability. In the Vertico bridge, channels for the girder segments and tendons were opened; on the other hand, in the external-cable reinforced bridge, even though it is a similar segmental bridge, the need for cavities is reduced because the cables are passed externally. In terms of strength, since the external cables carry the tensile load, less reliance on the high tensile capacity of the material is required; the material strengths of 80 MPa and 50 MPa respectively confirm this.

Similarly, the Striatus bridge built in 2021 and the Phoenix bridge built in 2023—described as its improved 2.0 version—carry formal and methodological similarities (Figure 36), and therefore offer data potential regarding the development of the method used. The arch geometry of the Striatus bridge is steeper, while in the Phoenix bridge this arch form became wider and flatter. This change in geometry reduced the clear height beneath the arch from approximately 2 m to levels of 1.5–1.3 m (Dell'Endice et al., 2024). With this change, the new design eliminated the need for steps and produced a more accessible design, although it limited passage beneath it. This situation shows that 3D concrete printing technology reshapes design decisions not only in terms of production ease but also in terms of urban context and usage typologies.



**Figure 36.** (Left) Striatus (Dell'Endice et al., 2023) and (right) the Phoenix bridge (Dell'Endice et al., 2024).

In the Phoenix bridge, the block sizes were reduced and their number increased. This was stated to provide convenience in transport and assembly. The installation time, which was 35 days including transport, was reduced to 3 days in the Phoenix bridge (Dell'Endice et al., 2024).

## 4. Conclusion and Suggestions

Based on this study, the following conclusions can be drawn:

- In bridge production, additive design through three-dimensional production methods achieved a maximum span of 16.6 m and a minimum production time of 48 hours. This demonstrates the advantage of additive production for fast and structurally efficient design.

- Among the examined examples, the hollow section was frequently preferred as the cross-section form. With an efficient form, the material is also used efficiently, which results in economy in the structure.
- Over the years, external-cable bridge prototypes have been developed in order to support disassembly and re-installation and to contribute to construction economy.
- Among the production methods, 3D concrete printing technology was mostly preferred, and the robotic arm was preferred as equipment. This confirms, in the context of bridges produced with this method, the observation reported in robotic-production studies that the robotic arm is the most preferred equipment.
- In all productions, admixed or high-strength concrete was preferred as the concrete material.
- In parts with hollow sections that lack an internal infill geometry, sand filling was used during printing to prevent collapse. This emphasises the importance of efficient geometry for applicability.
- Three-dimensional printing technology, which is widely used in the production of complex-shaped and small-scale objects, has, with the development of the technology and hence the capacity of the machines over the years, made the production of larger parts possible. Unit element sizes began at 2 m in the IAAC Madrid bridge. However, for ease of manoeuvring and application during on-site assembly (as in the Striatus and Phoenix examples), smaller and more numerous parts are also seen to be preferred.
- During the application of the bridges, temporary support girders and formwork are seen to have been used on-site.
- When the structural designs of the ten bridges are examined, it is seen that five bridges were designed in arch form and unreinforced, four bridges in flat form together with post-tensioning elements, and one structure was built in shell form.
- As stated in the Xiang Phoenix bridge study, there are no regulations or standards regarding 3D-printed bridges, which are structures that require load-bearing and safety preconditions. It is emphasised that, as a result of these trials becoming widespread between 2017 and 2025, such standards may be needed in the future.

The examples examined in this study reveal the advances achieved between 2017 and 2025 in the material, production time, and assembly strategies of robotic and three-dimensional concrete-printed bridges. Applications such as geometric optimisation, reduction of part sizes, external-cable tensioning solutions, and the use of local or recycled materials strongly demonstrate the potential of these technologies in terms of both sustainability and construction economy. However, for these developments to evolve from temporary prototypes into permanent structures, it appears inevitable that the data obtained from experimental processes be shared in a way that contributes to standardisation, that regulations regarding production and material performance be established, and that long-term performance analyses be carried out at the urban scale.

In this respect, the present review complements the existing literature rather than duplicating it. While process-oriented reviews such as Zhang and Sanjayan (2025) systematise 3D concrete printing for bridges according to printing-process categories and material-handling technologies, the case-based and paired-evolution approach adopted here foregrounds architectural design decisions, on-site assembly strategies, and integration with architectural education. Read together, the two perspectives—engineering-process classification on the one hand and project-based architectural evaluation on the other—offer a more complete picture of where 3D-printed bridge construction stands and where it may develop. In this context, it is anticipated that 3D concrete printing and robotic production techniques will become not only an innovative field of research but also an effective part of safe and sustainable architectural practice.

More specifically, this review contributes to the literature in three concrete ways. First, by compiling and cross-referencing all documented 3D-printed concrete bridges realised between 2017 and 2025 into a single, consistent comparative framework (Tables 1–5), it provides a ready reference point for

future case-based studies, which was previously scattered across individual project reports and disciplinary-specific publications. Second, through the paired comparison of formally and methodologically related bridges (Vertico–external-cable bridge; Striatus–Phoenix), it makes explicit a developmental trajectory—showing, for instance, the measurable reduction in installation time and material strength requirements achieved between successive design iterations—that is not addressed by process-category-based reviews. Third, by explicitly linking the identified technological trends (e.g., hollow-section optimisation, external tensioning, modular disassembly) to architectural design and educational practice, this review offers a foundation for integrating 3D concrete printing into architecture curricula and design studios, an aspect largely absent from the predominantly engineering-oriented literature on the subject.

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The article was written by a single author. There is no conflict of interest.

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