

# A Framework for Large-Scale Structural Applications of 3D Printed Concrete: the Case of a 29 m Bridge in the Netherlands

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# A framework for large-scale structural applications of 3D printed concrete: the case of a 29 m bridge in the Netherlands

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**Abstract.** In this work, a framework for large-scale structural applications of 3D printed concrete is presented, which serves as an important step to develop a regulatory basis for approval in the Netherlands. The steps in this framework, consisting of a design phase, testing phase and manufacturing phase, towards a final output were presented and discussed theoretically. The framework was then applied to the case of a 29 m 3D printed bridge, funded by Rijkswaterstaat Major Projects and Maintenance, constructed in the Netherlands. The full application of the framework illustrates that despite the absence of standards, it is possible to safely apply 3D printed structures in practice. With the gradual increase of testing data expected to become available over the coming years, the extent of the application of the framework can be reduced step-by-step.

**Keywords:** 3D concrete printing, bridge, protocol, testing, mock-up

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## 1. Introduction

The digitization and industrial automation of various production stages have supported productivity growth in the manufacturing industries [1,2]. Over the past decade, many manufacturing industries have reaped the benefits of the process and product innovations from the fourth industrial revolution (Industry 4.0) and implemented novel digital technologies such as augmented reality, 3D scanning, robotics, and additive manufacturing (AM) [2]. The latter, also popularly known as 3D printing, has been adopted by key manufacturing industries such as the automobile and aerospace industries to improve capital gains through material optimization with product customization [3]. The potential of AM has been recognized by the architecture, engineering & construction (AEC) industry, too, as a method to fulfil the industry's inherent demands for a higher productivity, and reduced environmental impact. In the AEC industry, AM can be applied to manufacture structural and non-structural elements with various materials such as concrete, wood, ceramics, steel, polymers, foam, glass, and other building materials [4]. At the moment, concrete is the most widely used 3D printable material in the construction industry [5-7].

However, scaling up the 3D concrete printing (3DCP) technology to apply it in the construction of houses or infrastructure projects comes with its own set of challenges. Despite all the progress made over a short period by various research groups and companies the world over, the application of 3DCP in the AEC industry is still in its infancy: current (showcase) projects demonstrate the potential, but cannot yet compete economically and

there is much to be gained in terms of environmental footprint. The issues related to the scaling of objects and standardization of the technology need to be addressed by codes and protocols with high priority [8], as existing regulations are not directly applicable to 3DCP without further consideration. Technology-specific characteristics such as the lack of compaction by vibration, or the layering and associated anisotropy, are not considered. Specimen sizes and geometries are not always suitable. Moreover, the consistency of structural properties when printing under varying conditions, with different equipment or operators, is mostly unknown. International associations such as RILEM, ASTM, and *fib* have only recently begun addressing these developments. Standardization requires sufficient, reliable data and a sound understanding based on actual project experiences. In this latter area, in particular, there is a dire lack of publicly available information.

To address this gap and start developing protocols for standardization, Rijkswaterstaat (the executive body of the Dutch Ministry of Infrastructure and Water Management) Major Projects and Maintenance together with the Eindhoven University of Technology (TU/e) has initiated an experimental valorization project. The project aims to study the challenges of applying 3DCP technology in an actual structure of significant size, namely a bicycle and pedestrian bridge with a total span of 29 m, in the city of Nijmegen. In addition to common requirements of bridge performance, two project specific demands were set. Firstly, the bridge would feature a size and design freedom that constituted a significant improvement over a previously realized 3DCP bicycle bridge constructed in the Netherlands [9]. This required the development of a process for the bridge design, which could fulfil the design requirements within the limitations of 3D concrete printing technology. Secondly, the bridge was to be used as a case to study the effects of scaling up 3DCP technology and its performance in a real-life project open to public use. A validation methodology had to be developed for the generic design and construction of similar projects in the future, which facilitates the approval process by authorities.

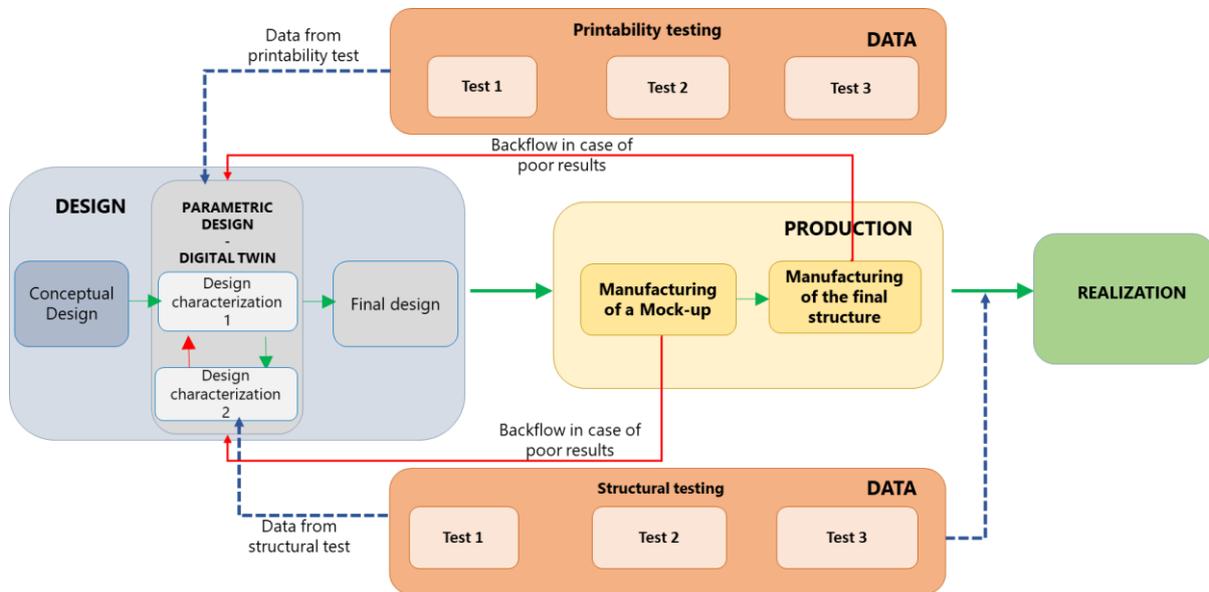
The current paper presents the design and mock-up phase of this bridge, with the aim to further demonstrate the viability of the applied design concept to realize moderately sized bridge structures with additive manufacturing of concrete by extrusion layering, in addition to previous studies [9-11], but on a larger level of scale. On a more general level, this paper intends to contribute to the development of generalized methods for design, calculation, testing, and approval of such structures, by presenting an overall framework of design and structural validation, in which the work has taken place.

## 2. Framework for the design methodology

Although it is obvious the extrusion-based 3DCP technology provides a wealth of hitherto unfeasible geometrical design opportunities, which can be used for aesthetical, functional, or structural purposes, it still does have specific limitations as to what is and what is not possible to make. An extensive discussion of these limitations falls outside the current paper's scope, but the shape-making method based on continuous linear stacked filaments dictates a certain design logic that has to be adhered to [7]. Considering this from the design start significantly reduces extensive redesign mid-stream that could weaken the original design intent. Therefore, an explicit design and validation framework was developed that could be applied to this project, as well as similar ones. It allowed for a relatively efficient design and approval process without excessive trial-and-error and is schematically represented in Figure 1. The framework is broadly divided into four blocks:

- Data,
- Design,
- Production, and
- Realization.

They are further detailed in the following subsections.



**Figure 1.** Framework illustrating the validation methodology for 3DCP structures.

## 2.1. Data

In comparison to conventional construction projects, the framework is characterized by the data blocks, one related to aspects of printability and the other to mechanical properties. Covering information on printability on the one hand (top block in Figure 1), and mechanical properties data on the other (bottom block in Figure 1), they inform the design block with the data needed to develop the design. While such information is normally readily available from codes, guidelines, supplier data sheets, text books and so on, this needs to be explicitly established for the 3DCP method. At the start of the project, some data on both was already available, but in order to develop an increasingly efficient design methodology, the data block is supplied with additional testing data from the production and realization blocks during the project.

## 2.2. Design

The design starts with formulating and outlining the structure's requirements regarding functionality, aesthetics, structural performance, budget and so on. Similar to conventional construction, the discussions on the requirements are translated into a conceptual design idea in the form of a 3D computer-aided model (CAD) model for the structure. However, much more than in conventional processes, the construction method (3D printing), the material behaviour and geometric design should be considered in an integral fashion in this digital model, as they influence each other and thereby the quality of both the printing process and that of the final, printed result. The model of the conceptual design should thus consider various technological limitations, structural, printability, and material requirements. In this framework, the digital model is developed through an iterative process based on a parametric design platform. This avoids a trial-and-error design of the overall structure. The data underlying this model (stored in the data blocks) can be acquired through mixed approaches and methods based on mainstream experimental testing on printable concrete, empirical observations, previously conducted research projects. This allows for a more robust understanding of learning environments [12-14].

Existing data on the parameters are fed into the parametric model to create boundary conditions within which the structure can be realized. Based on the structure's required design characterizations, the parametric model can provide design iterations until a satisfactory result is achieved. Besides providing a manufacturable design, the parametric model also provides a digital platform to store the data from the tests on the structure. Furthermore, the model offers the possibility to store data from every project, by updating the established correlations between printing strategy, material behaviour and structural behaviour of the printed object in the parametric tool, thereby making the model more efficient with each project.

### **2.3. Production**

Although the results from printability and mechanical testing provide a basis to estimate the manufacturability of the full-scale objects, this can only definitely be established in the production phase itself. As the design is developed based on data from generic tests, project-specific and scaling issues [15] might arise (e.g. material quality deviations due to prolonged printing, plastic deformations in large elements, compatibility with other construction materials). Hence the production is divided into two stages.

The one-to-one scale construction of a mock-up in the first phase helps to identify any unforeseen parameters related to manufacturing in the design phase. As mock-ups are intensive both in terms of associated costs and efforts, the appropriate item of which to make a mock-up of, has to be carefully selected through engineering judgment, based on what part of the structure is considered governing in complexity and structural performance, and what mock-up design is expected to provide the most information relative to the cost. The mock-up construction provides the opportunity to combine and test the learning from various printability test and design decisions from previous projects. The other significant activities carried out during the mock-up construction is to document and develop protocols. Documentation of conditions such as temperature, time, and humidity, which may impact printing the elements, assembly, and logistics, is essential to provide learning for future projects. Studying the influence of the conditions related to the mock-up construction also provides the opportunity to develop quality control protocols during the structure's final realization. Upon completing the mock-up, various tests associated with validating the mock-up's performance are carried out.

If satisfactory results are achieved from the mock-up testing, the protocols developed during the mock-up construction are followed to manufacture the final structure. However, in case of unsatisfactory results from the mock-up test, the whole process is reviewed and re-designed starting from the parametric design phase to either construct a new mock-up or proceed to develop the final structure in case of minor corrections from the mock-up construction. During the manufacturing of the final structure, the process related to documentation and quality control should be carried out to improve the data associated with the manufacturability of 3DCP structures. Over time, the necessity for a mock-up should reduce and eventually become obsolete with increasing data becoming available from previous projects.

### **2.4. Realization**

Fulfilling the *'living laboratory'* role of the bridge, it will be subjected to on-site testing before final placement as well as to in-use monitoring to provide additional input to the data blocks which will help to develop standards and codes of practice for scaling up 3DCP technology in general.

## **3. The case of a 3D printed bridge**

The framework will be illustrated for the case of the 3D printed bridge in Nijmegen. In this work, the design, manufacturing and testing of a mock-up is considered. The full-scale pro-

duction and assembly of the bridge was performed by the industrial parties involved in the project, based on the findings reported in this study (but not discussed here).



**Figure 2.** Design for the bridge designed by Michiel van der Kley [16].

The bridge's design (Figure 2) was developed by Michiel van der Kley, and TU/e performed the research on the printing process and structural testing. The structural design of the bridge was developed by Witteveen+Bos consulting engineers, for which Summum Engineering developed a parametric design tool. Finally, the bridge's manufacturing and assembly are realized by the joint venture 3D printing facility of Saint-Gobain Weber Beamix and BAM constructions.

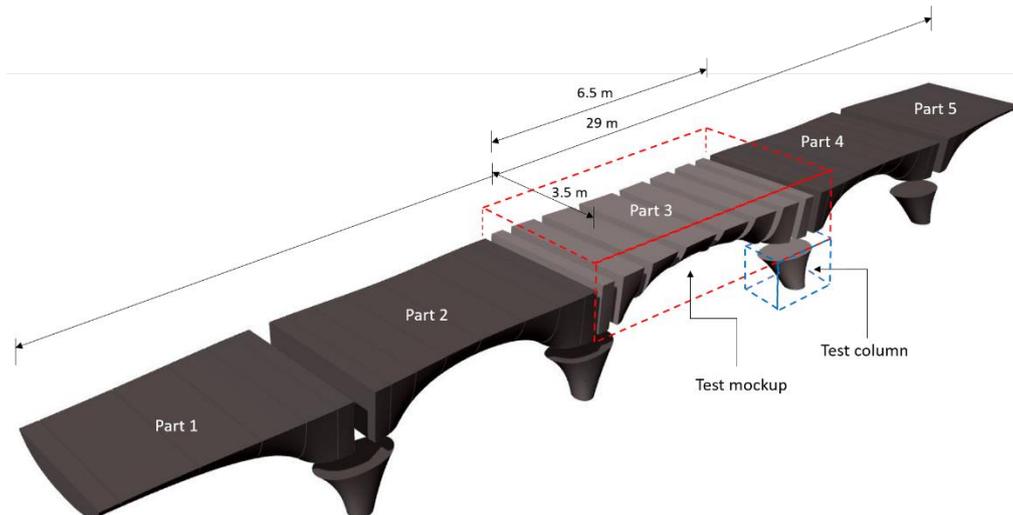
### **3.1. Conceptual design of the bridge**

The bridge design is based on a double curved deck that spans across tapered columns, which appear to be sprouting out of the deck. This nature-inspired shape illustrates the freedom of geometry enabled through 3D printing, near impossible to manufacture efficiently by traditional construction techniques.

### **3.2. Structural principle**

Like the 3D printed concrete bridge realized in Gemert, the structural principle is based on the assembly of multiple printed elements joined together by prestressing tendons. This principle eliminates the necessity of passive reinforcement along the bridge span, as the prestress level is selected such that exclusively compressive stresses remain active in each section due to occurring bending moments. The 29m span of the bridge was divided into five simply-supported parts, each spanning between 4.5 to 6.5 m, resulting in a configuration of multiple statically determinate girders. Each of these five girders is enclosed by two anchor blocks, which introduce the prestressing force into the 3D printed concrete. The five girders were further subdivided into smaller elements due to manufacturing and logistic constraints. Contrary to the previous bridge project, each element's geometry is unique due to the bespoke, double-curved bridge design. As such, each element has a width of 3500 mm, and a height varying between 700 to 1200 mm (Figure 3). These elements are glued together in the assembly stage.

The cross-section of each of the elements consists of a series of connected bottle shapes, alternatively positioned upside down illustrated in fig. 5. The exact geometry (e.g. number of bottle shapes, size) followed parametrically from each element's dimensions and was designed to resist occurring shear forces. All 'bottles' are connected via a continuous line at the bottom. This principle of non-solid sections has already proven its value in the previous bridge project of Gemert and allows for a reduction of material use and weight while simultaneously providing openings along the bridge span for the prestress tendons to run through.



**Figure 3.** Tessellation of the Nijmegen bridge.

Each part consisting of multiple elements, as shown in figure 3, is enclosed by two anchor blocks at the ends. These blocks consist of conventional reinforced concrete, cast into a 3D printed concrete 'lost formwork' to achieve a consistent texture appearance. Unlike the cross-section of the girder segments, the anchor blocks were realized as solid sections to distribute the prestress force into the printed element evenly and prevent high stress concentrations in the relatively slender, printed layers.

The anchor blocks rest on four pairs of columns along the bridge span and two traditional abutments at the bridge ends. The columns are designed as reinforced concrete elements and are, like the anchor blocks, cast into 3D printed lost formwork. These columns are fixed to a pile foundation. From a structural engineering perspective, they may be treated as conventional reinforced concrete columns and are therefore excluded from structural testing and further discussion.

### 3.3. Structural validation

Structural engineering consultancy throughout the project was provided by Witteveen+Bos consulting engineers. Using Finite Element Analysis (FEA), the bridge girders were modelled as 3-dimensional structures built from curved shell elements (rather than volume elements, to reduce modelling effort and computational time). In projects, such as this, where 3DCP elements are applied as part of the main load-bearing structure, data on structural material properties are limited, particularly concerning the interaction with process parameters, which is significant [17]. Scale effects may also occur [15] and suitable reinforcement technologies are still under development [18]. The print mortars themselves generally contain a high amount of cement and only small aggregates, resulting in a high shrinkage and low friction resistance in cracks. The layered structure may introduce anisotropy and variations in print settings can influence the properties of the printed product. The lack of formwork printed objects requires specific attention to curing conditions. Furthermore, the topology of 3DCP elements, characterized by relatively thin-walled parts with open space in between, introduces a number of potential structural risks unfamiliar to conventional concrete structures. It may lead to local instability phenomena and a loss of load redistribution capability (and hence susceptibility to stress concentrations, geometrical accuracy, and deviations between structural models and reality). Furthermore, it is likely these geometries result in differential shrinkage due to uneven dehydration and temperatures throughout an element. In turn, this may cause forced deformations and thus cracking.

Current structural codes and guidelines do not take these effects into account, and are thus an insufficient basis for structural design and approval. In recognition of the need to provide innovations with a potential path to the construction market, articles 4.2 and 5.2 of the Eurocode 0 *Basis of Design* [19] allow the possibility to develop structural designs partially based on project-specific experimental testing, rather than generalized calculation rules alone. Annex D 'design by testing' further details the type of experiments that can be performed and regulations on the statistical evaluation of results. It distinguishes 7 categories of tests that can be applied, but due to the necessarily general nature of this Annex, it only provides minimal instructions on the embedment of such experiments into the design and validation process. Based on the possibilities thus offered by the Eurocode to deviate from generalized calculation rules, a testing protocol was developed containing the following approach.

Initially, a set of mechanical tests was performed to obtain relevant structural material properties (Annex D, category b) such as the compressive strength, flexural strength, and modulus of elasticity of the material. The characteristic mechanical properties of the applied material, a commercially available print mortar (Weber 3D 145-2), have been established in an extensive experimental program [17] and further expanded with additional tests on samples from new batches of the same material, according to the same methods. The tests were performed in multiple directions, on printed samples. The data (stored in the 'data' block of the framework) were used to define the final dimensions of the bottle-shaped cross-section and the required prestress level of the tendons. The ultimate limit state (ULS) has been calculated based on the common load factors in NEN-EN 1992-1-1 and the mechanical properties.

Subsequently, a full-scale mock-up was prepared (as part of the 'production' block of the framework). New material samples were prepared during the printing of the mock-up elements, and subjected to additional mechanical tests to verify the previously obtained material properties (category b/e). The mock-up itself was subjected to a full-scale destructive test (category a/d), which is discussed in Section 5. After evaluating the material and full-scale tests, the production could be approved. Since all of the girders were designed following the same structural logic, only one representative part of the full bridge was considered for the mock-up testing, designated as 'Part 3' in Figure 3.

The protocol further specifies that material samples are again taken at the final element production for verification (category e), while the final bridge is to be subjected to a diagnostic test (i.e. a loading until the ultimate limit state load) before being taken into use (category g). Material samples are cubes of 40 x 40 x 40 mm and prisms of 40 x 40 x 160 mm, in accordance with mortar testing codes, as the print material mostly resembles a mortar rather than a concrete, and these dimensions are furthermore appropriate for the typical wall thickness of 3DCP elements (40 – 80 mm). The behaviour of the bridge will furthermore be monitored during its service life, to timely recognize potential long-term degradations and adjust the prestress in the tendons if necessary (category g). The successful completion of this protocol formed the basis for approval by the local building authorities. To reduce uncertainties in future projects, all material tests (initial, mock-up, production) were collected to extend the database on material properties.

### **3.4. Printable design**

The structural design of the bridge was further refined following conditions related to the bridge's printability. The capabilities and limitations associated with the 3D concrete printing system at Eindhoven University of Technology (TU/e) defined printing and manufacturing constraints for the bridge design. For example, considering logistics and lifting capacity, the segmentation of the bridge girders into smaller elements was based on the limit value of 4000 kg. The TU/e 3DCP system has been extensively discussed in [7], based on which printing strategies were developed to overcome the printing limitations and improve the degree of design freedom according to the bridge's design ambitions.

With regard to the print process parameters, basic printing settings had to be recalibrated to the larger scale of the project. Normally, the 3DCP printing facility of the TU/e is used to print filament widths of 40 – 60 mm, and 10 mm height. To obtain the 80 mm wide filament required in this project, the print mouth opening was redesigned and consequently settings such as print head travel speed and pump frequency had to be reset to obtain a smooth filament. In relation to the filament width, the minimum radius of in-plane curves was re-established. Most importantly, a method using a granular inner support material was developed to print doubly curved geometries in the u,w-plane (separately published as [20]). The results of these tests served as input for the development of a printable design, particularly for the parametric model used during the design. When initial designs for the various bridge parts had been developed based on these studies, full scale trial prints were performed as some effects cannot be simulated on a small scale. This resulted in some adjustments of the design (see Section 4).

Following the constraints of the general strategy of 3D concrete printing by stacking layers vertically, the bridge girder and column elements had to be printed with different printing directions compared to the direction of final assembly on site. Like the 3DCP bridge at Gemert [9], the girder elements have been printed along the cross-section and were rotated 90° after printing for assembly. The columns were positioned by flipping them 180° to the direction of printing. However, to maintain continuity in the bridge design's double curved form, the transition between girder and column required special attention since the angle of curvature at the connection was relatively large.

## **4. Manufacturing of the mock-up**

The mock-up manufacturing was conducted in three phases: printing a column, printing the girder segments, and constructing the anchor blocks. Finally, the overall assembly of the mock-up and quality control protocols developed during the printing phases are discussed. All mock-up printing was performed using Weber 3D 145-2 printable mortar, and a 60 x 12 mm backflow-flow nozzle. The geometrical shape and properties of the nozzle are discussed in [9]. The extruded filament's width was increased to 80 mm, compared to the nozzle opening, by reducing the print speed and increasing the extrusion rate, with the aim to improve the object stability during the printing process.

### **4.1. Column printing**

A mock-up column was printed to evaluate the significantly cantilevering geometry's buildability, calibrate the corresponding print settings, and test the infill support material. Only after the geometrical limits had been established, and were incorporated into the parametric design tool, the final shape of column as well as of the connecting girder could be defined. The column layering was horizontal, but the column was printed upside down (i.e. from top to bottom) such that the infill material would support the internally cantilevering shape.

However, despite the application of a temporary support material, the initial column design was still susceptible to failure during printing, as one side of the column was partly straight and even slightly curved outwards, and thus unsupported. Due to the relatively small column circumference, and corresponding rapid vertical building rate, the fresh material was loaded (too) quickly and failed due to object instability at the unsupported part during printing, illustrated in Figure 4, left.



**Figure 4.** Failure during printing of the initial column design (left) and successful printing of the adjusted column design (right).

Following analysis of the failure mode, the geometrical restrictions were fed back into the parametric model and the design of the column was updated, such that the infill material would support the column across its full height. Subsequently, the column was printed successfully as shown in Figure 4, right.

## 4.2. Printing of girder elements

Considering the maximum lift capacity of the printing facility, the girder was tessellated into six separate segments which were printed individually. Each segment had comparable weight, and since the print path length per layer varied, thus a varying overall height. These bridge segments had significant curvatures along their outer geometry, which, despite the relatively long contour length, could lead to similar failure as observed in the column printing trials. To address this issue, the segments were positioned such that any cantilevering would occur inwards and could thus be supported by infill material. The straight parts on the other side of the elements (i.e. along the bridge deck) were not supported to minimize additional labour. A close-up during printing and an overview of a printed segment is shown in Figure 5.



**Figure 5.** Printing of a girder segment with support material.

The printing settings were selected such that, similar to the column, the filament width of the girder segments was equal to 80 mm. The heartline distance between print paths in the horizontal (print) plane was, however, reduced to 65 mm to create an overlap in the printed filaments. This was done to avoid cavities in the printed geometry and maintain adequate bonding between two horizontally adjacent layers. Such overlap does result in collection of fresh concrete in front of the nozzle during printing, which had to be removed periodically by hand. The girder segment's print path strategy was based on following a spiral-based continuous contour of closed-loop layers over the whole printed segment. Each layer was composed of the required bottled shaped print path to support the structural design requirements of the

internal geometry. The (vertical) transition between each layer is achieved by gradually moving the print path from the first layer to the layer above to maintain a smooth layer transition.

Based on this manufacturing strategy, each of the six girders' segments was printed successfully. After printing, each element was covered in plastic sheets for a curing process of approximately one week. The foil was only temporarily removed to lift the elements from the print bed, which took place at least 48 hours after they had been manufactured.

It should be noted that, while the adopted support material strategy improves the printing freedom, adding the material manually during the printing process is a tedious process, in particular for large geometries such as the girder segments. For industrial applications, it is recommended to develop an automated system to introduce the support material instead.

### **4.3. Construction of anchor blocks**

The anchor blocks are positioned at both sides of the (six) printed segments and were composed out of conventional, reinforced cast concrete, to withstand splitting tensile forces caused by the prestress tendons. To maintain consistent overall appearance, the anchor blocks were poured in a 3D printed mould that acts as a lost formwork, similar to the column strategy discussed above. Locally, the 3D printed concrete formwork was removed such that the poured concrete of the anchor block was resting directly on the poured concrete of the columns. This way, any peak stresses caused by the layered texture of the printed lost formwork were avoided.

### **4.4. Assembly of the girder**

The assembly process of the girder segments and the anchor blocks was carried out following the procedure developed for the construction of the 3DCP bridge at Gemert [9]. The elements were flipped 90° from the printing direction and assembled horizontally in the direction to be placed on site. However, due to the girder's double curve shape (contrary to the straight elements of the Gemert bridge) a temporary scaffold following the curvature of the bridge girder had to be constructed upfront. The elements were placed one after another on the scaffold and assembled. Each interface between two adjacent segments was glued with a synthetic epoxy-based resin to level out the uneven top surface of a printed segment and avoid local stresses once loaded.

Like the Gemert bridge, the mock-up was prestressed by straight, unbonded post-tensioning tendons. Due to the curvature of the bottom side of the girder, the prestressing tendons were concentrated in the top part of the cross section, such that the tendons could pass through the internal bottle-shaped structure of all the mock-up segments without touching the printed layers. The tendons were placed in two rows, nine prestressing tendons in the top and six tendons in the bottom. The final step was to lift the assembled girder and place it in a testing rig for the large-scale mock-up test.

### **4.5. Data collection and quality control**

Developing protocols for data collection and quality control is an integral part of the design and manufacturing in this bridge project. Hence, during the manufacturing, different quality control checks were performed to document the quality of the process and that of the final product. During the printing process, sensors were placed on the printing system to collect temperature data. For relatively long printing times, as is the case for the bridge girders, large fluctuations in temperature could affect the quality of printed concrete as discussed in [21]. Similarly, the environmental conditions such as relative humidity were logged. For manufacturing of the bridge mock-up, these values were found to be approximately constant during individual printing sessions, and between printing days (all performed within the time span of two weeks).

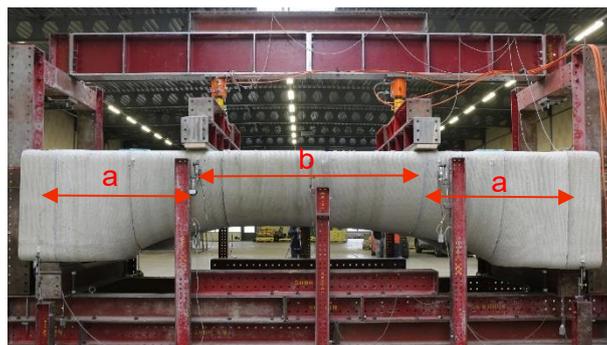
To validate the expected structural performance of the girder segments, during printing, the filament dimensions were measured periodically, as changes in the layer dimension might influence both the global resistance and the self-weight of the bridge mock-up (which is the dominant load case on this bridge). Where needed, to maintain the required layer dimension, countermeasures are adopted by adjusting the printing speed and the extrusion rate to achieve the desired layer dimensions. Moreover, following the protocol for structural validation, material samples were taken during printing of the girder segments to validate expected material properties.

## 5. Structural test of the mock-up

To assess the structural performance of the 3D printed bridge and validate its compliance to the safety regulations, one 3D printed and pre-stressed girder of the bridge spanning between columns was subjected to an experimental testing program on a 1:1 scale, designated as the 'mock-up test'. A single girder, with a total length of 5875 mm, was subjected to a four-point bending test, whereby the distance between the loading and support points was varied in two configurations, to validate the bridge resistance towards both bending moment and shear stresses.

The test set-up of the bridge girder is illustrated in Figure 6. In the first configuration (designated as T1700), the distance between the support and loading points  $a = 1700$  mm, such that  $b = 2475$  mm, to assess the girders resistance towards the applied bending moment. In the second configuration (T1000),  $a = 1000$  mm and  $b = 3875$  mm, thereby increasing the ratio between shear and bending stresses, which allows for an assessment of the shear resistance of the girder.

For both configurations, the applied loading was based on the ultimate limit state. For configuration T1700, this resulted in a maximum loading of 100 kN at each loading point, whereas for T1000 each point was loaded up to 115 kN. The loading was applied via two hydraulic jacks in steps of 25 kN at a loading rate of 0.25 kN/s per jack. The girders were fully unloaded in between steps, at a rate of 1.00 kN/s per jack, to evaluate whether damage has occurred in the structure. The top of the girder was locally capped with self-levelling mortar to evenly distribute the loading over its full width.



**Figure 6.** Setup of the structural mock-up test.

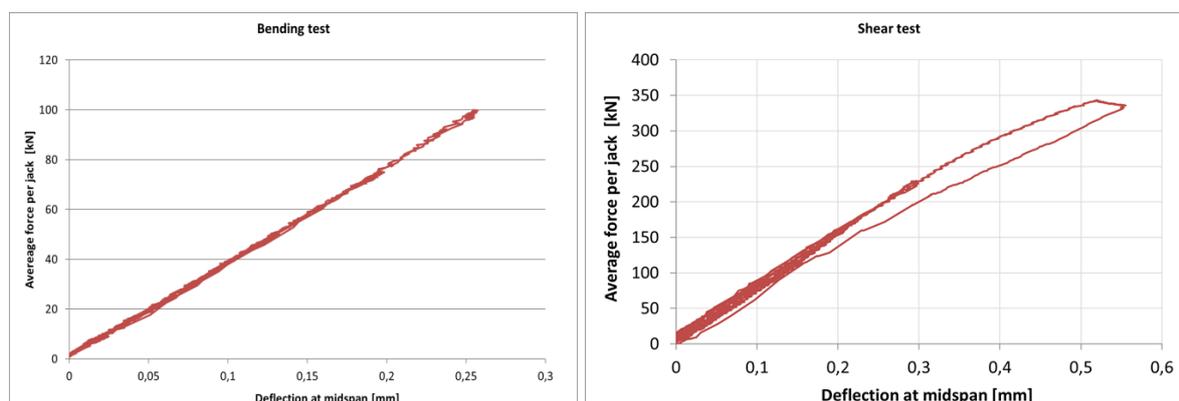
The test with configuration T1700 was performed first, after which the girder was fully unloaded, and the setup was changed to configuration T1000. Once the design load according to the ULS was then reached, the loading in this configuration was further increased to 345 kN per loading point. This additional step was performed to gain insight into the occurrence and type of damage, and the possible presence of warning signals before failure. Throughout both tests, the load was recorded by means of 350 kN load cells position at the loading points, and vertical deformations were measured at midspan on two sides of the girder by LVDT's. The prestress level was monitored at 4 tendons, two at the girder top, and two at the

bottom. This level was found to be constant over the duration of both tests, and is thus excluded from further discussion.

It is noted that due to this particular bridge design, a direct load transfer to the supports is not unlikely in the T1000 configuration. This will have a positive impact on the girders' shear capacity, and should be considered in the analysis of tests results, and in particular, when designing similar structures with larger span to depth ratios.

## 5.1. Results

Figure 7 shows the load-displacement curve of the tests in configuration T1700 and T1000, respectively. Here, the force per jack is plotted versus the averaged vertical deformation at midspan. The results of both tests show a perfect linear elastic behaviour throughout the complete loading-unloading sequence, up to the load level corresponding to the ultimate limit state (ULS). After each loading step, the curve returns to zero displacement, indicating that no damage, and thus no loss of stiffness, has occurred. For the regime beyond the ULS loading level, tested in configuration T1000, the linear elastic behaviour is observed up to approximately 260 kN per jack. From this point on, a slight non-linear deformation behaviour is observed up to the maximum applied load of 345 kN. No visible cracks were observed however. It is noted that this change in behaviour occurred well above the required minimum capacity. After reaching 345 kN per jack, the test was stopped, as three times the loading level of the ULS was reached without occurrence of failure. While it would have been insightful to observe which failure mode would have occurred, the limit of the measurement equipment was reached and the risk corresponding to sudden release of energy was too high.



**Figure 7.** Load-displacement graphs of the two loading T1700 (left) and T1000 (right).

In configuration T1700, the loading points of 100 kN each resulted in a bending moment capacity of  $M_R$  of 170 kNm and an additional shear resistance capacity  $V_R$  of 100 kN for external loads. Similarly, in configuration T1000, the applied loads of 345 kN each resulted in a bending moment resistance capacity  $M_R$  of 345 kNm and an additional shear resistance capacity  $V_R$  of 345 kN for external loads, for this particular girder design.

From the experimental program, it may be concluded that the mock-up of the bridge performed well and that the structural capacity is sufficient. A bending of resistance of two times the ULS load was found, without failure occurring. Likewise, a shear resistance of three times the ULS load was achieved, although the contribution of direct load transfer is not known. The tests moreover confirmed that the serviceability limit state (SLS) requirements are well met, as the deflections in both configurations were minor.

## 6. Bridge assembly and diagnostic test

The satisfactory results of the mock-up test demonstrated that the bridge design fulfilled the structural requirement, and production of the full bridge was commissioned, and performed by the industrial parties involved in the project in correspondence with the manufacturing strategy applied for the production of the mock-up, illustrated in Figure 8. In accordance with the framework proposed here, the full 3D printed bridge has been subjected to an in-situ diagnostic test. The difference with the mock-up test is that this time the bridge girders are not loaded to failure, but to a load that gives enough valuable information about the safety, without causing unnecessary damage. Based on the structural response found in the mock-up test, it was chosen to load the bridge girders up to 100% of the ULS load, since a linear elastic response was found in the mock-up test and the same behaviour was expected here. Since each of the six girders can be considered as a simply supported, statically determinate system, they were all tested separately such that six diagnostic tests were performed. The loading was applied by means of water tanks, which were filled in steps of 25% of the full load. After each step, the deformation was measured at five points along the span, on both sides of the girder. A detailed description of the process of printing, assembling and testing of the full bridge falls beyond the scope of the present work.

## 7. Conclusions

In this work, a framework for large-scale structural applications of 3D printed concrete is presented. The steps in this framework, consisting of a design phase, testing phase and manufacturing phase, towards a final output were presented and discussed theoretically. The framework was then applied to the case of a 29 m 3D printed bridge, constructed in the Netherlands. The full application of the framework illustrates that despite the absence of standards, it is possible to safely apply 3D printed structures in practice. However, it is not desirable from the perspective of cost and material use to be required to conduct such large-scale tests for every 3DCP project. The framework now offers guidance for application, but as soon as the quality of 3D printing processes can be sufficiently assured, the intermediate mock-up test phase can be dispensed with. In this stage, a diagnostic test of final object will suffice to validate the expected structural performance.



**Figure 8.** Assembly of the final bridge on location

Eventually, once the structural behaviour of 3D printed concrete can be assessed, through analytical models, numerical analysis or via codes of practice, as is the case for conventional concrete structures, the diagnostic test can likewise be omitted. In this final stage, experimental characterization of the material quality will remain as part of the quality assessment of the 3D printing process. To support this transition, it is imperative that the relatively young community in the field of 3DCP shares the lessons learnt and results of these first illustrative projects. This contributes to the development of understanding of the structural behaviour of

printed structures, and provides a basis for standardization in the field. The framework discussed in this paper serves as a starting point to conduct this in a uniform manner.

## Data availability statement

The testing report of the mock-up phase is available upon request.

## Author contributions

**Z.Y. Ahmed:** Investigation, Methodology, Writing original draft. **R.J.M. Wolfs:** Conceptualization, Writing – review & editing. **F.P. Bos:** Conceptualization, Writing – review & editing. **T.A.M. Salet:** Conceptualization and Supervision

## Competing interests

The authors declare no competing interests.

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