

BE-AM

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Additive Manufacturing

2020
SYMPOSIUM
EXHIBITION

BE-AM 2020 SYMPOSIUM AND EXHIBITION



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INTRODUCTION

FOREWORD

ULRICH KNAACK & OLIVER TESSMANN

Since the first BE-AM Symposium in 2015, Additive Manufacturing has gone through a tremendous development at a breathtaking speed. A large variety of construction materials have been tested for additive processes in research and practice worldwide. Buildings have been printed in Europe, Asia, and the USA. This year's BE-AM symposium invites speakers and participants to speculate and extrapolate how AM will change the construction industry in the coming years and decades. Furthermore, we want to exemplify and discuss strategies of integrating AM and 3D Printing into larger and more complex process chains. Within architecture and the building sector. Be-AM 2020 seeks to cover the full range from 3D scanning existing contexts to novel forms of ideation and design methodologies that fully exploit the newly gained potentials to finally materializing innovative constructions

BE-AM | Built Environment – Additive Manufacturing 2020 is a digital symposium and video exhibition that brings together international experts from research and industry.

Participants present and discuss the current status and future potential of additive manufacturing for the construction industry. BE-AM is an annual event at TU Darmstadt since 2015. This year's symposium is the second year we teamed up with the Formnext Fair to be a strong dissemination and knowledge exchange platform.

This small publication collects the projects of BE-AM participants that have either presented or exhibited their work. We feel honored that these brilliant thinkers and makers participated, and we hope to inspire you as a reader.

Q&A



Q&A PROF. URLICH KNAACK DR. WILSON RICARDO LEAL DA SILVA

Ulrich Knaack (UK) : Right, so Wilson, Who are you?

Wilson Ricardo Leal da Silva (WR) : Well, I'm a Dr. in Civil engineer working on 3D Concrete Printing and several other topics at the Danish Technological Institute (DTI) – it's as simple as that.

UK: Simple as that, right. So, what do you Print? What is your Interest?

WR: My personal interest is finding sustainable solutions for 3D Concrete Printing. At the very beginning of my work in this topic, the main idea (at DTI) was "hey, let's make something printable using cementitious materials". That was, you know, the first step in the whole process of understanding how to adapt digital fabrication technologies, robot controlling, pumping systems and so on in order to realise a printed concrete element. We need a good control and mastery of all of the aspects in the process. Whenever we presented the work we were doing at DTI, there has always been a request, especially from concrete producers, who would tell us "Ok, we see the potential there, especially when it comes to material savings and productivity, but can you actually print with concrete – meaning... Can you print with large aggregates?" That is what we, at DTI, are moving towards now – We are developing concrete mix designs that are as lean as possible (in terms of cement

content) and that has large-aggregates . This involves a lot of challenges of course.

UK: So not just sand and cement, but also large-aggregates? And what do you define as large aggregates?

WR: Yes, we are testing and printing with large-aggregates. The last prints we were doing had 8mm aggregates. But, you know, concrete producers always want more! When you say I can do with 4mm, then they say we want 8mm. When you present with 8mm, they say, humm, can you go 16mm.

UK: of course

WR: But this is a development process and we are taking a step of a time.

UK: Are there any other concrete printing units dealing with this? Are there others doing larger aggregate printing as well? I can't remember!

WR: As far as I am concerned and publicly available information shows, the first ones who actually "surfaced online" regarding the use of large aggregates (when I say large, I mean over 8mm) was actually Army Corp of Engineers in the US. Later on, the first BOD (Building on Demand) built by COBOD also used large fraction of aggregates. They were using crushed tiles in



their mix design, and a fraction of it happened to be above 8mm, somewhat by coincidence - but they were the first ones in Europe! (Note: I am referring here to extrusion-based processes)

UK: So you're doing this to reduce the cement and sand – to really get towards a typical concrete mixture – it really tries to get towards a proper concrete mix.

WR: Yes, whenever I post something on concrete printing online, the reaction is always "Oh, but this is a mortar, you can name it as you wish before calling it concrete – but that is not concrete". They indeed have a the point, but the name 3D Concrete Printing is used in such a broad scope that it is hard to call it something else without causing confusion. In any case, whenever you go to a ready-mix concrete plant or pre-cast concrete manufacturer and talk about 3D concrete printing, they ask for large aggregates. However, I see there is space for both concrete and mortars in the realm of applications; for example, for architectural applications you could still use fine mortars for formwork printing (so you're printing the shape and relying on casting actual large-aggregate concrete inside), or you could start thinking of using "real" concrete – large-aggregate concrete – for producing load-bearing elements which need to be reinforced. This is a development topic that everyone goes after at the moment.

UK: Which is the second question I'm going to ask; So, larger aggregates – clear. What is the challenge to get these larger aggregates inside? I'm assuming the extrusion nozzle is the key parameter to allow this.

WR: Well, regarding the extrusion nozzle one of the many challenges is actually surface finish. This is quite tricky when dealing with larger aggregates (at high contents – similar to conventional concrete mixes)! If you're using some blades (trowels) for finishing the surface right after extrusion and these blades suddenly hit a large-aggregate, there is a risk that the aggregates is just going to be dragged along it and cracking and tearing the surface rather than finishing it

There is also much more equipment wearing. Say you're printing for long sessions; this means, you're not

printing smaller elements but, rather, a full house. Then there's a lot more friction between the aggregates and the pumping system over time. As a result, there's a lot more wearing and heat being developed due to high friction, this means there should likely have some pauses in the process (i.e. it is not running 24-7).

And finally, if you want to make a mix which is so lean that you're really reducing the paste and mortar content to value equivalent (or as close as possible) to conventional concrete, you get a mix in which you have to be extremely careful during the extrusion. There is very little room for playing around – because, again, if you extrude too fast then you start having this shark skin-like tearing effect and if too slow you, you lose control of the geometry of the extruded layers. At the end of the day, optimal mixes have to be both lean (sustainable) and robust in order to cover various boundaries conditions during printing.

UK: True, I get your point. Then, obviously next question – we always get this question when it comes to concrete printing. We know all concrete has to be reinforced, what's your vision about that?

WR: I had the pleasure of being one of the people giving a wrap up of the day in the Digital Concrete 2020 conference of one of the sessions which was also addressing reinforcement. The session I covered was mostly on fibre reinforcement (and there has been a lot of research on that over the past year). There was also a whole group (in a parallel session) working on reinforcement in terms of how to add re-bars. That is extremely tricky – the best solution I've seen so far is still the one from TU Eindhoven using a (steel) filament during the print. Though it still doesn't tackle the problem of transversal reinforcement, which is still a bit of a headache! (This means, there is space for innovation and research!). In our N3XTCON project at DTI, we have come with some concepts such as first mounting the rebar and then having the robot "dancing" around it and print with mortars / concrete, but there are still the issues such as anchorage (proper encapsulation of the rebars) and the actual bond length to get material coverage around the whole rebar. It's also very hard to match a quality which is as good as concrete which is cast onto formwork, but I



can see there is a lot of research effort towards this effort lately.

UK: Are you familiar with the research of Harold Kloft in Braunschweig which is spraying concrete onto the rebar and structure?

WR: Yes, I had the pleasure of visiting them last year and lecturing in a workshop about digital fabrication with concrete. Their approach is by far one of the best solutions I have seen, this is because they use a spraying method (rather than extrusion), and this provides enough pressure of the material against the rebars, thus guaranteeing a proper bond between concrete and rebar.

UK: Ok, next chapter. What about industry? Obviously the concrete industry is interested because they want to sell their product, but you named it sustainable concrete printing. How do you make it sustainable and what does industry take out of this?

WR: Most of the work that's been done on concrete printing at present (at industrial scale) is based on dry-

mix mortars (premixed materials). I don't know the full formulation of them (and when I do, I cannot disclose), but if you compare those dry mortars to conventional concrete, it's hard to compete on the kilo-for- kilo CO2 emission level. This is because there are know to have so much binder in it, let alone a cocktail of admistures, and that, at the end of the day, makes their cost sky-high (comparatively to conventional concrete). When I say sustainable in 3D Concrete Printing, I mean that there is a need to develop a framework for anyone who buys an extrusion-based printer to be able to develop their own mix-design based on locally available materials. I believe that at some time we will have guidelines for making concrete printing mixes; very much like we have guidelines for self-compacting concrete, fibre-reinforced concrete and so on, using locally-source materials.

UK: Ah I see, so sustainable is more in the A) less cement and B) more aggregate being added to the mix.

WR: Not only that, but also being locally-available!

UK: By that you're right, in that concrete can be seen as using less transport needs. I get that, interesting argument! So, Danish Concrete Industry – how do they tackle 3DCP?

WR: Oh, we actually have a development project which started in 2019! The N3XTCON project. In a nutshell, the project cover two tracks; one for using concrete as pre-fab for architectural elements and the other is for house printing. Both are trying to solve the issues of reinforcement equation in the whole system, while also working on simulation models. In general, the cement and concrete industry in Denmark are quite positive and supportive in using 3D concrete printing – they see the potential. BUT, the main point is that the entire process (from materials to printing technology) has to be robust, and if you don't reach a robust level that matches what you see in existing practices, then the printing process (as a whole) is not seen as productive. So, we're working with many companies like CRH Concrete, Aalborg Portland Cement, COBOD, Henning Larsen, BIG Architects, DTU and SDU. We're all putting our minds together to see

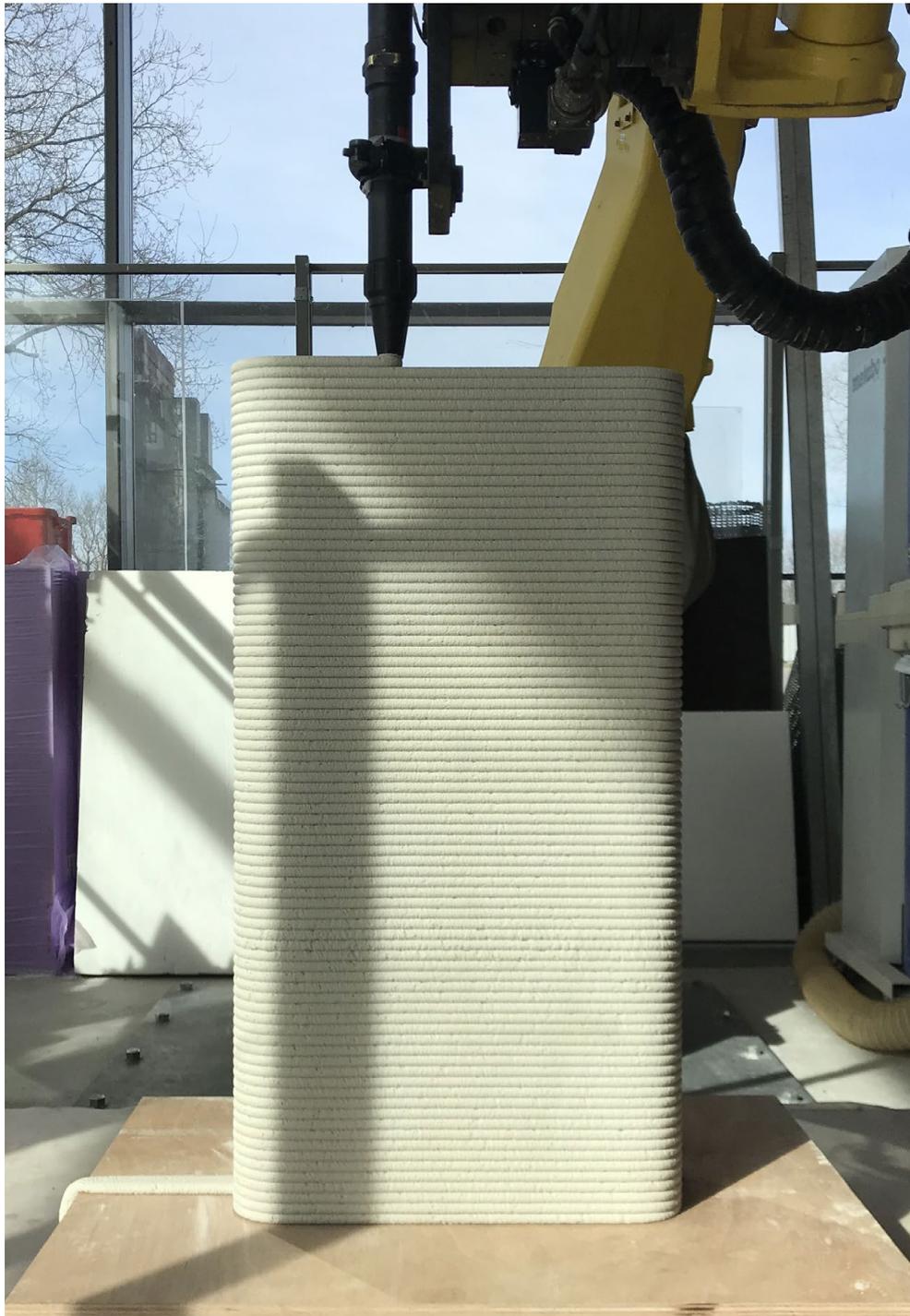
how we can deliver robustness and predictability to what we're actually printing whilst having this sustainability umbrella on top of everything. That's really a high priority on the Danish Environmental Agenda, let alone the construction industry itself (i.e. CO2 reduction or greener constructions) - especially when you look at the impact of climate change resulting from the construction sector alone.

UK: Clear, concrete is a clear target on this list. What are your next steps and challenges to solve over the next two years?

WR: To solve over the next two years?? Well, in such a short term, I guess reinforcing concrete is the main challenge which has to be addressed, and I mean a solution where the result of what you print is actually your load-bearing element.

UK: And you think this is going to be solved in the next two years?

WR: I'm extremely optimistic! I mean, you can always



go around the rebar challenges; and that is what most companies are doing right now, printing a shell, casting the concrete into it as formwork. The easiest solution at a glance would be to use concrete instead of mortars and proceed in the same way, casting concrete onto a shell (printed with concrete). Now, deploying a system in which everything is integrated, i.e. your reinforcement plus concrete printing, is a bit more complicated... maybe we need three years! We never know, we can always be surprised with new and unexpected developments that are not publicized.

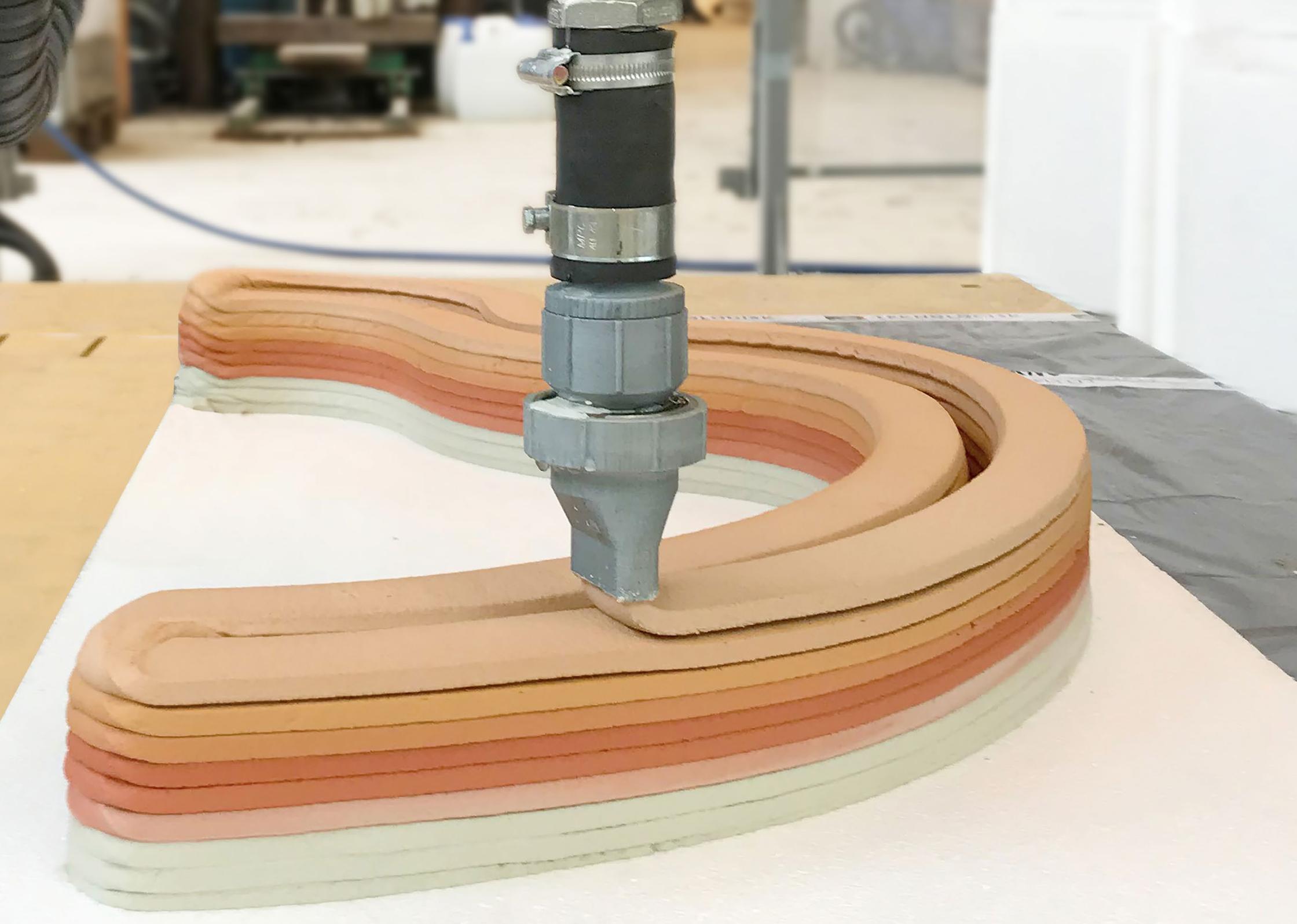
UK: Right! Then, what about in 8 years? Imagine you have all the money you want, that you can print all you want; what would you expect to happen in this concrete printing world?

WR: Within a 5 to 10 year's timeframe I would look more towards standardization. So, 5 years would see the initiation of standardization fronts (even though there's a lot of a suggestion for test protocols and characterizations

being published), and 10 years we would see a complete standardization. Within these 5 – 10 years, durability will also be a very strong topic of research. If we follow the research roadmap of 3DCP, we see a lot being done in terms of understanding and predicting fresh concrete properties, right now reinforcement is gaining a lot of attention, and the next topics to follow up are most certainly related to hardened properties and durability – there's actually very little research looking into durability.

UK: A very engineering like answer! Design-wise, are we going to see the first 10 houses printed in a small village?

WR: Oh yes, that's for sure, especially when you consider the materials and equipment that are available for today. In fact, this is a reality already. Likewise, seeing that being realized with a sustainable concrete solution is very likely in less than 5 years, so... I would say for sure!



ESSAYS



TOPOGRAPHY OPTIMIZATION BY TWENTE ADDITIVE MANUFACTURING

JON CAFTEN
TWENTE ADDITIVE MANUFACTURING
LACSIESTA@GMAIL.COM

For most construction sites the key to building an accurately assembled structure starts at the foundation. For thousands of years humanity has almost exclusively held the notion that you must only erect structures on flattened earth. There are of course exceptions to the rule from history in very difficult terrain when groups would need to fortify in the hills from invaders such as the architectural feats of Kaunos of Anatolia, Machipichu of Peru and the Ellora Caves of India. Even in these cases, great effort was made over hundreds of years to cut away stone outcroppings to make their terrain flatter.

There is a modern desire of course to build difficult structures without destroying the original geography. These elaborate buildings are often motivated to be demonstrations of construction extravagance such as the Doolittle home by Kendrick Bangs Kellogg, the Messner Mountain Museum by Zaha Hadid and the Two Hulls home by McKay-Lyons Sweetapple. Almost always though, great pains need to be made to tame the rock outcroppings or else the structures are just cantilevered over the irregular terrain.

Twente Additive Manufacturing has undertaken a massive project to use digital manufacturing for the first time ever to 3D print with concrete a series of structural elements that will join the naturally occurring rock without any disruption. This article is a brief introduction

to their concept and testing methodology that will be the foundation of a commercial project starting in early 2021. They chose a site in British Columbia, Canada that would provide a challenging set of variables to prove their theories on how this new technique will work.

The process first required Twente to take a digital scan of the lake-side site located near Nelson in a small community called Procter. This particular site is on steep terrain that has very little soil on top of two ridges that are comprised predominately of granite. The surrounding mountainside is forested however the trees cling to the hills with their roots grabbing any cracks in the rocks they can find. There is not a lot of loose material around to be used as fill so the site was an ideal candidate for Twente to push the boundaries of understood building methods in such adverse geography. (Figure 1)

For the scanning service they hired Harrier Aerial Surveys who used flying drones and ground mounted laser scanning equipment to create a 3D plot field with resolution down to the mm. Using a MS50 scanning total station and a DJI M210, Harrier used the Leica Infinity and Pix4d mapper software to sort the data. The point cloud formed from the Leica laser scan and the point cloud generated from the photogrammetry software were overlaid and combined to generate both a large area model and a detailed area around the bedrock.



Figure 1

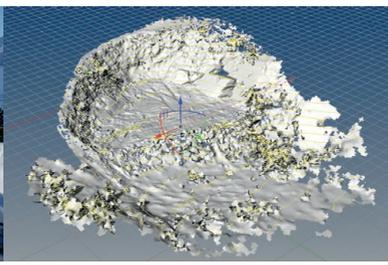


Figure 2



Figure 3

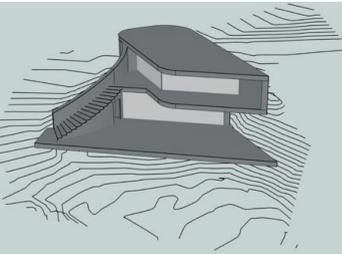


Figure 4

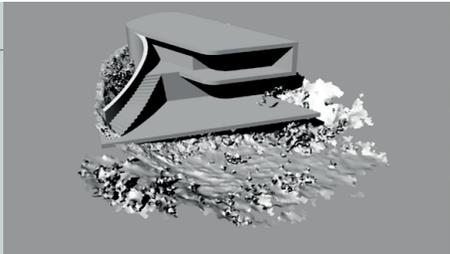


Figure 5

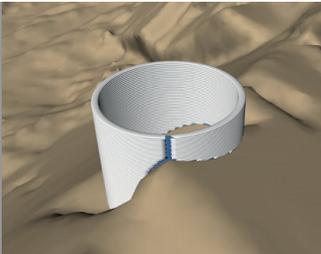


Figure 6



Figure 7. Test part placed on bedrock. [photo:I.Comishin]

Once this compiled data was cleaned by the scanning team, the resulting point cloud was imported by Twente's head of engineering Jonathan Ladouceur into Rhinoceros CAD software for further processing. (Figure 2)

The point cloud file was converted to a mesh file and trimmed to the targeted areas. Jonathan then took this plot data and worked alongside Jim Ziemiński to develop a home that could be 3D printed and placed on the site.

They started with sketches from the designer Peter Boeckeler at Spearhead Timberworks. From these conceptual drawings a foundation and slab strategy were designed so that the final building could nest into the half-moon shape naturally occurring just above the water's edge. (Figure 3, Figure 4 and Figure 5)

This is where things start to become revolutionary. As previously mentioned, it is normal to build on flat so usually bedrock would need dynamite or massive excavation equipment to clear a flat surface before the foundation could be built. Tim Brodesser used the building design provided by Jonathan and Jim to narrow in on an anchoring technique that the world has never seen before. Using the information from the laser scan

Tim created a part file that will come off of their concrete 3D printer. (Figure 6)

At the Twente Additive Manufacturing R&D facility, they use a 9-axis machine that can be fit with different nozzles and pumps depending on the printing mortar of choice. The element on the print bed is positioned upside down so it will flip into place on the rock outcroppings to create the planar surface that the rest of the structure will be built upon.

At the time of this publication the represented home to be built was still going through the permitting process so Tim created a print file exclusively for BE-AM to demonstrate this strategy invented by Twente. In this particular application a two-component mix was used which means that a liquid accelerator (6.5%) is injected into the mortar at the nozzle allowing for rapid curing. The column shown here is a leave in place mould that was printed in 6 minutes and 54 seconds using Baumit 230 Printcrete which is a build rate of 3.6m/hour. The total volume of the formwork is 101.53 dl and has a cured mass of 24kg.

The printed element normally would then be placed on the bedrock that has been drilled to allow for an insert dowel to embed into the formwork. Conventional

concrete is poured in and the foundation support is completed upon the completion of the 28 day cure cycle.

As this is only a demonstration for this article it should be explained that the final shape and positioning is not accurately represented. Rather than a round column, the house will sit on a series of footings that will follow the rocks edge along a given elevation based on the final house drawings. Normally Twente would laser scan the prints prior to placing them however as the deadline for this article was looming Tim chose to just place the part without 3D scanning the print. (Figure 7)

Everyone was pleasantly surprised when the printed element fit in perfectly despite the scalloping effect created by 2.5D printing. The top surface was perfectly level and the undercut feature showed that the multiple angles used for scanning gave a very accurate plot field as reference geometry. (Figure 8 and Figure 9)

Twente predicts that the time savings and cost savings of this new strategy will allow for people all over the world who live in steep rocky terrain to be able to erect houses without destroying the naturally laying topography. A new construction technique that would otherwise be only for the rich and famous or those who have 150-200 years to be able to carve into the rock walls.



Figure 8



Figure 8.1



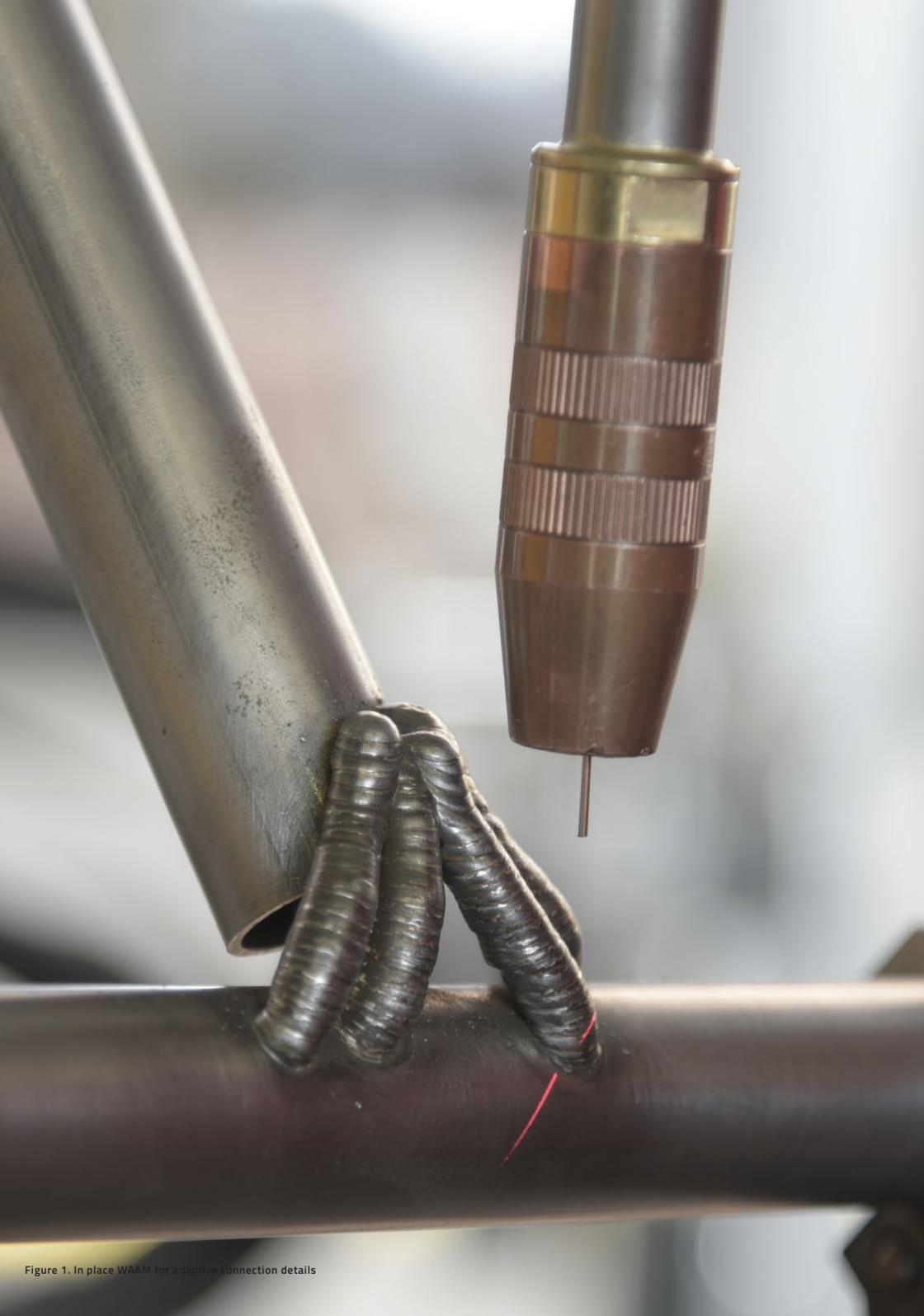
Figure 10



Figure 11



Figure 12. 3D printing process



TOWARDS ADAPTIVE DETAILING WITH IN PLACE WAAM CONNECTIONS

INÉS ARIZA*, ROMANA RUST, FABIO GRAMAZIO, MATTHIAS KOHLER
*GRAMAZIO KOHLER RESEARCH, INSTITUTE OF TECHNOLOGY IN ARCHITECTURE,
ETH ZURICH
STEFANO-FRANCINI-PLATZ 1, HIB E43, CH-8093 ZURICH
ARIZA@ARCH.ETHZ.CH

Introduction

Current developments in digital fabrication increasingly allow continuous control from the design to the materialized product. However, if we examine today's digitally fabricated architecture, in particular the contact interfaces between architectural elements, we often find that inconsistencies between the planned model and the physical output are still present, i.e. parts are not precisely the same or not exactly located where they are supposed to. This mismatch becomes evident in the joining detail, the place where parts are close enough for these differences to become visible.

While most of what constitutes the design-to-construction process is shifting with digital technologies, today's idealized CAD models do not yet contain all the information needed to process the constant changes of physical reality. This possible divergence between the planned and the built form is particularly relevant in discrete assemblies, where these divergences can accumulate. To this end, the concept of architectural detailing for assemblies has been evolving: what once was a resource to negotiate tolerances of standardized pre-fabricated components [1], today is aiming to become a system of material interdependencies [2]. Nevertheless, today most of the required information needed to process a suitable detail solution is modelled blindly: site information and material tolerances are

described as close as possible to what we expect to happen during construction [3]. Thereafter, connection details are typically manufactured and then assembled following instructions. But this fragmented approach is not fully functional to construction nor to design: computational design intelligence is lost in the transition of mediums. Even with the most robust and accurate detail model and the latest precision machining processes, differences at the assembly stage may still exist.

However, by integrating design and production phases, robotic fabrication might change how we think about connecting elements. In this research project, the robot's flexible and generic nature is integrated with sensing strategies to produce adaptive connection details that are adjusted during the assembly process. The detail's final geometry is now generated based on the information gathered from the current assembly configuration, eliminating the need of fully predefining a particular geometry, fitting or tolerance handling strategy. Gathering information from the current state of assembly, the adaptive detailing process devises the basis for a novel algorithmic framework for robotic fabrication of connection details.

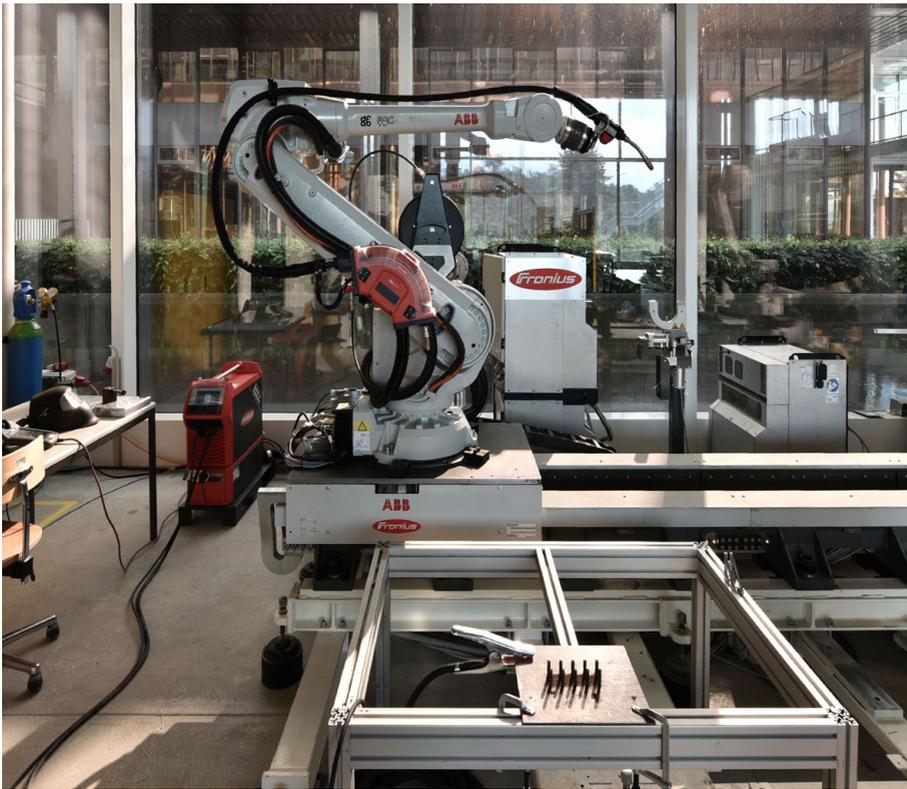


Figure 1a. WAAM fabrication setup

Adaptive fabrication

Adaptive fabrication refers to the techniques involved in surveying and adjusting a digital building process to compensate for divergences between planned and observed geometry [4][5][6][7][8]. These techniques rely on a combination of hardware and software technologies including sensing devices, closed-loop communication systems and algorithmic design platforms. Given that architecture is ultimately concerned with uncertainties related to site and material, adaptive fabrication approaches are key in the development of reliable digital construction [9].

The introduction of a large-scale multi-robotic setup at the Robotic Fabrication Laboratory at the Institute of Technology in Architecture at ETH Zurich has recently shown a new context of application

of adaptive fabrication [10]. This setup consists in multiple collaborative machines mounted on a gantry system, resulting in a high number of degrees of freedom for part manipulation in a large volume workspace. This technological leap has the potential to close an important gap in digital construction, finally allowing free and efficient placement of material at full architectural scale. However, the placing of material of performative assemblies typically follows non-repetitive geometric patterns. This results in a complex system of interdependencies relative to material behavior and geometric tolerances of parts that are hard, or sometimes impossible, to fully simulate in advance [11]. To overcome this challenge, our work investigates an adaptive, and in place joining strategy that re-computes the connection geometry



Figure 1b. WAAM fabrication detail of touch sensing to determine current location of layer height

at each stage of the robotic assembly process to handle unexpected variation due to imprecisions or deformations of the structure as it happens.

In place WAAM

The adaptive connection technique is explored through Wire and Arc Additive Manufacturing (WAAM), a metal 3D printing technique based on the same melting, fusing, and adding principle as welding technology. The WAAM setup is equipped with a robotic system extending the conventional process in three dimensions to precisely accumulate material in space (Figure 1a). WAAM is currently under development as a novel additive manufacturing technique in many research centers around the world [9]; however, the potential of using it as an in place joining method is at its early stages [12].

In place WAAM is characterized by depositing material onto referenced existing geometry. Due to the printing carried out in between other objects, the technique requires strategies to avoid collisions with existing parts and printed material. The degrees of freedom of the robot can help in this respect. However, a

flexible torch orientation entails appropriate design and toolpath calculation methods to ensure fabricability in the space obstructed by existing elements [13].

In place WAAM also faces the challenge of knowing the current location of existing part in space. Thus it requires sensing strategies for localization. In this project, two sensors are used to this end: first, we use a laser profile sensor to determine the location of base elements; second, we use the welding wire as a touch sensor to determine the position of the current layer height during printing (Figure 1b).

In place WAAM adaptive connections

Our work investigates an in place adaptive approach to connection details. In place refers to the production method: the proposed connections are 3D printed in its final location within an assembly, as opposed to connections that are prefabricated in a separate manufacturing process and then assembled [14]. Adaptive refers to its generation method: they are programmed as a set of responses to structural and manufacturing constraints, therefore their geometry is not predetermined and can be adapted during

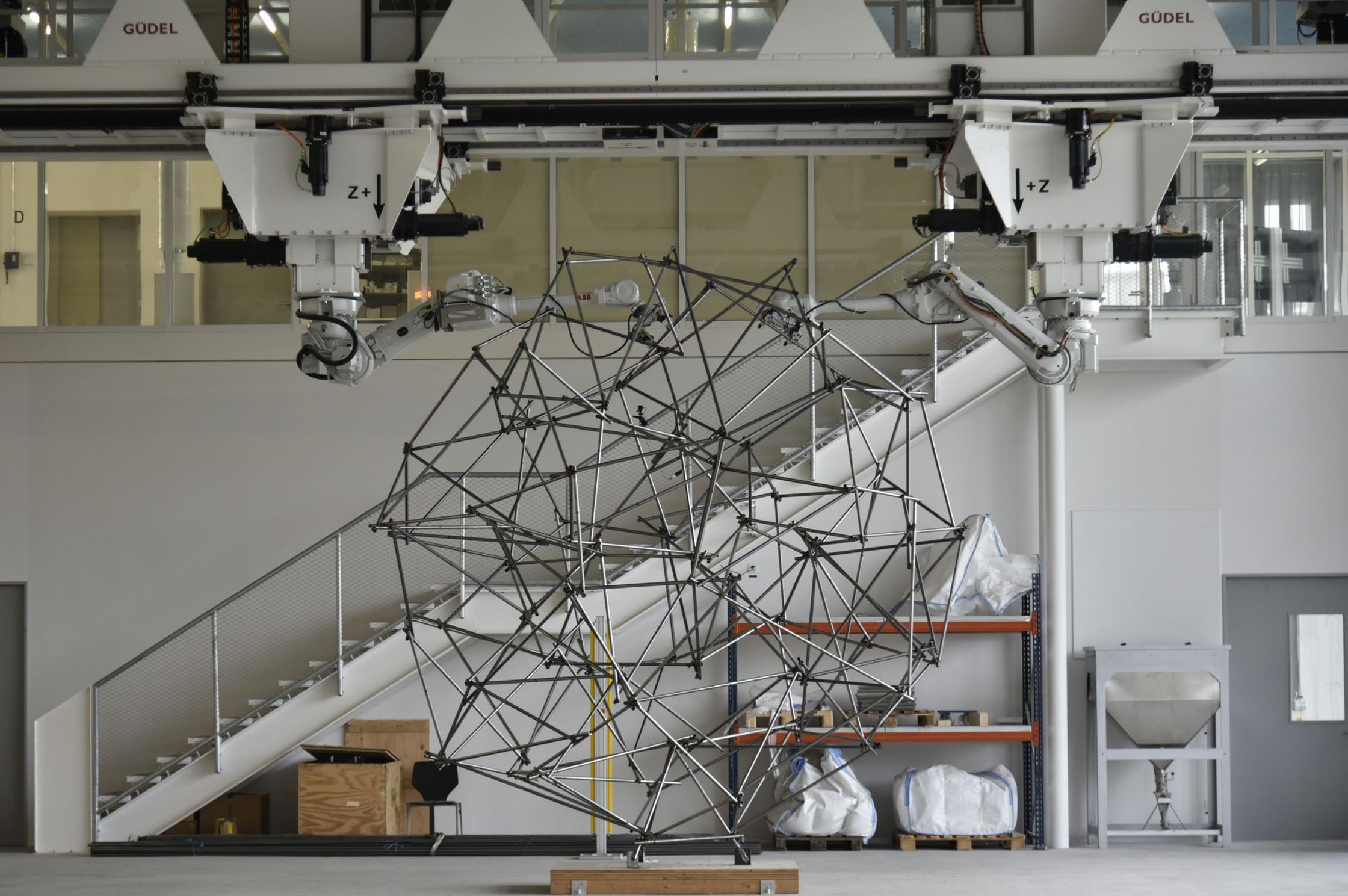


Figure 2. Cooperative Robotic Assembly, Gramazio Kohler Research 2018

construction.

The connection details studied here are tailored for standard tubular elements made of mild steel. The interfaces between these building elements are non-coplanar and can be in contact with each other, or have gaps in between due to accumulation of building deviations.

We are interested in exploring steel standard elements and WAAM for many reasons. First, steel structures are ubiquitous in architecture due to their structural performance (high strength relative to its weight). This ubiquity places the research of steel connections with a direct applicability in real construction. Second, industrial robotic welding is one of the most widespread robotic processes found in industry [15]. This aspect allows validating results with a large body of literature. Third, current research has demonstrated that the lightweight nature of steel is compatible with cooperative robotic assembly processes (Figure 2) [16]. Fourth, the relatively high-resolution of the WAAM deposition unit (as little as 3mm²) allows a precise control of the connection detail geometry, therefore enabling the placing of the joining material only where it is required. This aspect allows adapting the geometry during the buildup process. Fifth, the joining technique does not need a perfect substrate and is suitable for bridging a wide range of gaps, a convenient flexibility for handling tolerance issues found during assembly. Sixth, the high-deposition rate of continuous deposition of WAAM and the possibility to carry out the process in an open, non-controlled atmosphere (i.e. as opposed to other metal 3D printing methods) allow for a relatively fast and undemanding joining method.

Given a correct set of process parameters, the major constraint of the process is to keep the torch angle relative to the build-up vector as small as possible while avoiding a collision between the torch and the existing geometry. This aspect results in detail geometries that are larger in area than the typical welded connection, and are therefore more visible and expressive of the joining process (Figure 3).

Adaptive detailing with in place WAAM

The context of application of in place WAAM is the robotic assembly of self-supporting discrete steel element structures. These structures are composed of standard steel elements assembled in space in non-standard configurations without the need of external supports. The assembly is performed with two robots: one robot is used for positioning parts and another robot is used for joining the parts together. We call adaptive detailing the computational method for design and production of connection details that resolves their functional and manufacturing constraints in one integrated pipeline.

The adaptive detailing pipeline is structured in modules that are active according to the needs and complexity of each connection detail. The modules are structured in different categories: initialization, production, functional constraints, and fabrication constraints (Figure 4). The software environment builds on top of the COMPAS framework currently under development at the Institute of Technology in Architecture [17] and uses the core library and specialized packages for geometric modelling, structural analysis, and fabrication planning.

Conclusion

With the work presented here, we aim to contribute to current developments in adaptive fabrication techniques for robotic assembly of non-standard spatial structures. To this end, adaptive detailing contributes to this development looking at the connection detail as a dynamic coordinator of building data. The method structures the gathering, evaluation and processing of building information during the assembly process, as opposed to conventional fragmented workflows in architectural design, planning and construction.

Both the self-supporting nature and the lack of post-processing requirements make the WAAM process suitable for adaptive detailing. The connection details change according to its construction sequence, the need of adaptation to the actual geometric configuration of the base elements retrieved from the localization



Figure 3. In place WAAM for adaptive connection details

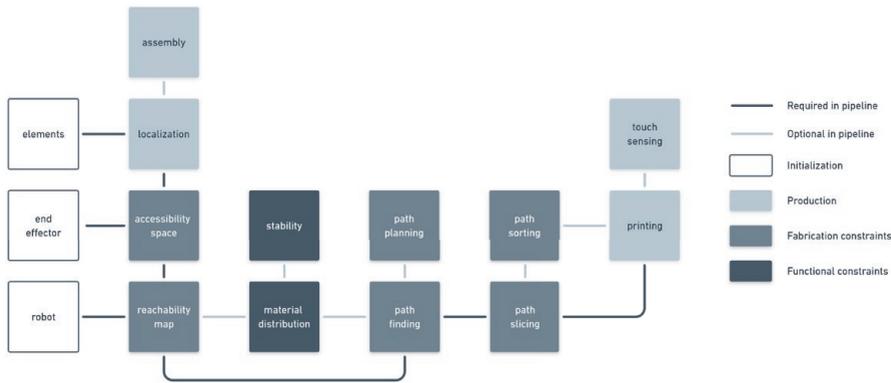


Figure 4. Diagram of modules for adapting detailing with WAAM

process, and the reachability of the connection location. The relatively small deposition volume of the WAAM process allows a precise unit of control of the detail geometry, therefore enabling local adaptation to the existent geometric configuration found during assembly that may differ from the connection modelled a priori. The availability of a detailing pipeline that can output solutions even if the construction process does not match the planned model can be a key advantage for the assembly of complex non-standard discrete structures where positioning errors critically accumulate.

Our case study in steel explores new concepts of adaptive detailing in relation to the structural, manufacturing and expressive properties of spatial steel structures suggesting new approaches to non-standard space frames. While the constraints explored in here are tightly linked to steel construction, the methods aim to provide a transferable basis for adaptive detailing for other discrete element building systems.

Project credits

Gramazio Kohler Research. Collaborators: Inés Ariza (project lead), Dr. Romana Rust, Gonzalo Casas, Dr. Ammar Mirjan, Philippe Fleischmann, Michael Lyrenmann. In cooperation with: Mathias Bernhard (ITA, ETH Zurich), Maicol Fabbri (IWF, ETH Zurich), Prof. Andreas Taras (IBK, ETH Zurich), Vlad Silvestru (IBK, ETH Zurich), Prof. Ueli Angst (IFB, ETH Zurich), Lucas Michel (IFB, ETH Zurich). Master students: Ioanna Mitropoulou (MAS dfab, ETH Zurich), Samuel Cros (MAS dfab, ETH Zurich), Julie Vienne (D-BAUG, ETH Zurich). Sponsors: Fronius Schweiz AG, voestalpine Böhler Welding. The project is supported by the Institute of Technology in Architecture and the NCCR Digital Fabrication.



Figure 5. In place WAAM adaptive connection detail



Figure 6. In place WAAM adaptive connection detail

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RE-PRINTING ARCHITECTURAL HERITAGE: THE HIPPOLYTUSKERK AND MAURITSHUIS PROJECTS

PROF. DR.-ING. CAROLA HEIN*, PROF. DR.-ING. ULRICH KNAACK

* DELFT UNIVERSITY OF TECHNOLOGY

C.M.HEIN@TUDELFT.NL

Abstract

Additive Manufacturing (commonly known as 3D printing) technology has become a global phenomenon. In the domain of heritage, 3D printing can be seen as a time and cost-efficient method for restoring vulnerable architectural structures. The technology can also provide an opportunity to reproduce missing or destroyed cultural heritage or to express lost appearances, in the cases of conflicts or environmental threats. Researchers from TU Delft have led two experimental projects published respectively in *Innovative Materials* (volume 6 2018 and volume 1 2019). The projects show the challenges and possibilities of contemporary 3D printing technology for the 3D printing of heritage. The first one, a 4TU-project called 'Re-printing architectural heritage' focused on the Hippolytuskerk in the Dutch village of Middelstum. There, the group of researchers tested available technologies to reproduce a mural on a section of one of the church's vault with maximum possible fidelity to material, colours and local microstructures. Simultaneously, a second project was conducted at the Mauritshuis at The Hague. This to investigate and to discuss the potential of reprinting historical spaces as a copy.

The Hippolytuskerk project

The 4TU project 'Re-printing architectural heritage' took the Hippolytuskerk in the Dutch village of Middelstum as a case study to explore the limits of existing technology and to research the possibilities of 3D printing of cultural heritage. Architectural historians, model building experts and scientists from the universities of Delft and Eindhoven have been involved in various aspects of 3D printing, with the aim of reproducing different parts of the 15th-century church. For example, the available techniques were tested to reproduce a mural in one of the vaults of the church, as faithfully as possible to the original material, the colors and the microstructure.

By combining new technological developments in 3D scanning and 3D printing with research in the field of architectural design, the project team aimed to create material reproductions of architectural heritage. Eventually, the team selected a painting of an angel riding a lamb in a vault by the choir. The painting shows the Last Judgment and is part of a series of scenes by Albrecht Dürer. During the section's scanning and printing process, the researchers encountered several challenges, ranging from the impossibility

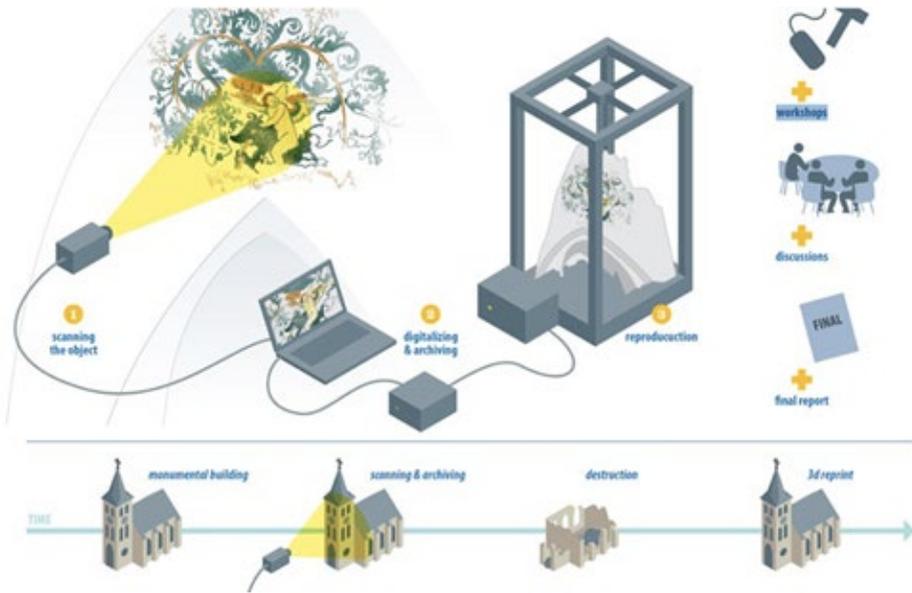


Figure 1. Infographic of the project re-printing architectural heritage (4TU Bouw)

of the scanning technology to capture the existing cracks in the required resolution, to the high cost of specialty printing with certain materials and the limited capabilities for combining printing techniques for such a complex structure.

Thin Film

In the absence of printing technology that can apply a color to a non-flat surface, it was decided to explore the opportunities of printing the painting on a thin film and applying it over a 3D printed structure with visible surface microstructures. In principle, the film print ought to take into account the deformation based on surface unevenness and curvature. While it is basically possible to generate a computer model deformation, the team decided to ignore this aspect for our pilot project.

Having separated the structural printing and that of the film, the researchers opted to first experiment with materials for 3D structural (non-colored) 3D printing. The CAMlab of TU Delft produced a first gypsum test print without color, providing a good first impression

of the surface structure. The scientists found that the thin lines produced by the gypsum print technology were insufficient to render the texture of a wall surface. Additional test prints were produced by QUBICX, to experiment with different materials.

Two methods

Two methods were tested: one with MultijetPrinting, another with Selective Laser Sintering. In the first case, a colored sandstone model was produced on the 3D systems ProJet660Pro. The printer builds the model layer by layer and applies a thin layer of gypsum powder to the print table. The colored binder is printed on the plaster layer, following the shapes of the model for that specific layer. The binder is printed on the plaster using an inkjet printing technique. This system is also known as MultijetPrinting (MJP). The color binder reacts with the gypsum powder that cures the material. After the print is complete, the unbound, unused plaster is removed for reuse. The printed object is then chemically post-processed resulting in vibrant colors and a strong

model. The second model was printed with PA12 white (nylon) produced on an EOSint P770 SLS 3D printer. The PA12 powder is spread layer by layer on the print table in the same way as the first model. Only this time the material is bonded using laser beams. The result is a very accurate and strong model, also known as Selective Laser Sintering (SLS). Both of these objects had the qualities necessary to serve as sub structure. To reduce the cost of the printing material, the team decided to hollow out the piece and to apply spider-like/honey-comb back structure.

For the front structure, several options were discussed. The inkjet option appeared to be not suitable for this project. The team therefore decided to print the final colors and textures on a thin flexible foil layer (50 microns) and fix it over the solid 3D structure, which in this case will have all the microstructures, and grains visible. Reducing the glossiness of the material as much as possible was one goal. To make the final product best resemble the church mural, we applied an additional matt layer. A 3D test print consisting of four panels was first exhibited at the Facade 2018 in Rotterdam in (January 2018). It has since been shown to the public at two other events.

Challenges

By combining 3D printing with a foil surface treatment, curators can experiment with reconstructions of paintings from different time periods, compared to the original. Such a comparison is especially effective when the print is viewed from a certain distance. However, a number of challenges remain. In this way, the foil retains a certain gloss that does not correspond to the original ceiling painting. In addition, the four panels that come together in the structure deformed during the drying process and the dividers remain visible despite the foil covering them. This problem is partly due to the thinness of the workpiece, which has been chosen in this case to save costs.

Proposals for a 3D print of a Middelstum church vault based on a new design could lead to a puzzle-like system that mimics the original decoration of the church. Such an



Figure 1a. On the left the 3D printed mural of the Hippolytuskerk van Middelstum; on the right the 3D printed section of the Golden Room of the Mauritshuis; both exhibited at TU Delft (Photos: TU Delft)



Figure 1b. The Mauritshuis 3D printed section



Figure 2.



Figure 3. Selection of the area to be printed

approach could be followed in future research and would take into account the specific material and technical qualities of 3D printing. Moreover, the technology used in this project is not the only one that has been tried out by the team. Research and a trial 3D print of part of the Golden Hall in the Mauritshuis have provided additional insights.

The Mauritshuis

The Mauritshuis is an aristocratic palace built in The Hague between 1633 and 1644, The Netherlands. Since 1822 it is a museum that houses the Royal Picture Gallery. The collection of Flemish and Dutch 17th century masterpieces is unique in the world. Due to its historical position for the Netherlands it was agreed to use this museum as a test case for the principle idea of reproducing a historical space by 3D-printing and to revive forms and colours that disappeared over the centuries.

Today, because of ageing of the materials, overpainting and renovations, the room looks very different from its original appearance. Margriet van

Eikema Hommes studied, together with the conservators of the Mauritshuis, the original appearance of the Golden Room and has developed 2D reproductions this state. The 3D print helps translate the theoretical knowledge obtained and results from the 2D reproductions, in spatial 3d reconstructions.

The 3D print features a section of the room in its reconstructed original state, thus recreating a long lost spatial and esthetical entity. They provide the viewer new insights on the visual impact of this ensemble, its conceptual unity, its pictorial vocabulary and changes in perception history over time. In this way, the project connects technological and humanities cutting-edge research. First it was necessary to define a suitable section with sufficient texture and colour and finally a part of the so called Gouden Zaal (Golden Room) was selected.

Physical product

Next, various additive manufacturing technologies were investigated regarding to their suitability. In addition to the possibility of gypsum-based coloured

components, plastic-based components were also investigated, which were coated with coloured foils. After examining a series of samples, a gypsum-based geometry was selected for this project. This promised the most accurate definition of colour and glossiness for the interpretation of the actual and historical space.

The next step was to physically create the selected section after digital processing. Due to the limitations of the dimension of the printers, it was necessary to divide the model into many components and to print these separately. In order to make the resulting cut lines appear as inconspicuously as possible in the model, cuts were made in such a way that they disappear into the geometric texture of the model.

Subsequently, the components were printed in their given geometry, texture and colouring and mounted on a supporting substructure. This substructure makes it possible to set up the resulting object as a stand-alone component. During the project, the process, the technologies and the first physical results were evaluated in different workshops. In addition, the physical result and process of the project were discussed and presented to a wider audience during the 'research week' of the Faculty of Architecture/TU Delft in November 2018.

Results

Related to the restricted budget and dimension of the printers, the limitations in quality and dimensions are obvious. It can be expected that with the development of more suitable technology and with an acceptance of the scientific and social potential, larger objects could be targeted to be reprinted.

Next to this, the quality of the printed results in texture, geometry and glossiness will increase and therefore allow a better likeness of original and reprint. The general results of the project do deliver the expected process and physical results and by that reflect the expectation and deliver a first sketch concept of the process, technologies and physical results. Next to the internal evaluation of these results a public evaluation and discussion of the results and their implication for future projects has to take place in future follow-up projects.



Figure 4. Subsequently, the components were printed in their given geometry, texture and coloring and mounted on a supporting substructure. This substructure makes it possible to set up the resulting object as a stand-alone component

Acknowledgements

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The projects became possible through collaboration among numerous participants:

Credits Middelstum project:

- Delft University of Technology: Prof. Dr.-Ing. Carola Hein;
- Dr. Michela Turrin; Prof.dr.ir. Joris Dik ; John Hanna, Miktha Alkadri, Serdar Asut,
- Prof.Dr.-Ing Ulrich Knaack; Peter Koorstra
- Eindhoven University of Technology: prof.ir. Juliette Bekkering, ir. Barbara Kuit
- Cultural Heritage Agency of the Netherlands: Albert Reinstra
- National Archives: Angela Dellebeke
- 3D idea printing – Dave Vanhove
- QUBICX: Dick Vlasblom
- Foundation for Old Groningen Churches: Jur Bekooy
- BLOMSMA PRINT&SIGN: Ron Teeuw -4Visualization: Valentin Vanhecke
- 3M Netherlands: Wim Oostveen

Credits Mauritshuis project

- Delft University of Technology
- Prof. Dr.-Ing. Ulrich Knaack (TU Delft)
- Prof. Dr.-Ing. Carola Hein (TU Delft)
- Prof. dr. Joris Dik (TU Delft)
- Dr. Margriet van Eikema Hommes (TU Delft + Materials in Art and Archaeology

& Cultural Heritage Agency of the Netherlands)

Partners:

- Dr. Edwin Buijsen (Mauritshuis Museum)
- Boy van den Hoorn (Mauritshuis Museum)
- Dick Vlasblom (QUBICX)
- Valentin Van Hecke (4Visualization)
- Miktha Alkadri (TU Delft)

Illustrations

Fig. Subsequently, the components were printed in their given geometry, texture and coloring and mounted on a supporting substructure. This substructure makes it possible to set up the resulting object as a stand-alone component

Fig. On the left the 3D printed mural of the Hippolytuskerk van Middelstum; on the right the 3D printed section of the Golden Room of the Mauritshuis; both exhibited at TU Delft (Photos: TU Delft)



HYBRID PEDESTRIAN BRIDGE PROTOTYPE COMPOSED OF METAL 3D PRINTING AND FIBER FILAMENT WINDING TECHNIQUE

PHILIP F. YUAN*, HOOISHAN BEHA

*CAUP, TONGJI UNIVERSITY / FAB-UNION INTELLIGENT ENGINEERING CO., LTD.
PHILIPYUAN007@TONGJI.EDU.CN

Abstract

The paper presents the design and fabrication of DigitalFUTURES 2019 robotic fabricated hybrid bridge, which is the third and most recent experimental robotic fabricated bridge project since 2017. The bridge structure, which spans 11.4 meters in length and 3.9 meters in height, was fabricated and installed with two sets of fabrication strategies using metal 3D printing for the bridge's primary structural base and fiber filament winding technique for the bridge secondary components. Such a hybridization approach aims to explore and develop an experimental lightweight and performative construction system under a 47-day tight schedule. Structural design techniques such as topology optimization, wire-arc additive manufacturing, and structural stress line analysis are used to realize such a structure. The design process of the hybrid bridge started from the initial structural design until the final assembling process design are outlined in this paper.

Introduction

The hybrid bridge was a project of DigitalFUTURES annual summer workshop held in Tongji

University. Since 2018, the pedestrian bridge has become the team's prototyping object tested with different materials integrated with novel fabrication technology. A few considerations are taken into account

as the key factors driving the selection of a pedestrian bridge as a prototype object.

First, a bridge is an architectural and engineering object that integrate form design and structural functionality; second, the prototype has a feasible fabrication scale that could demonstrate a printing process under the challenge of limited-reach of a typical 6-axis industrial robot; third, the team had to work on a tight month schedule including design and fabrication. Hence efficiency is an integral consideration in every stage of the workflow planning.

With a constant site and weather constraint for fabrication each year, the previous bridges in 2017 and 2018 have respectively showcased different fabrication strategies of using single material and single fabrication strategies such as 3D printing with modified plastic and latter using wire-arc additive manufacturing techniques with steel. Through experiences gained from these two projects, it was learned that the modified plastic bridge lacked structural durability. It embodied deformity issues under high temperatures, as described in [1]. In contrast, the steel bridge has an excellent structural performance yet coupling with disadvantages such as low efficiency on fabrication strategy as described in [2]. Combining these factors, the new bridge project for the 2019 DigitalFUTURES workshop attempted a hybridized approach to selecting materials and



Figure 2. DigitalFUTURES 2019 robotic fabricated bridge

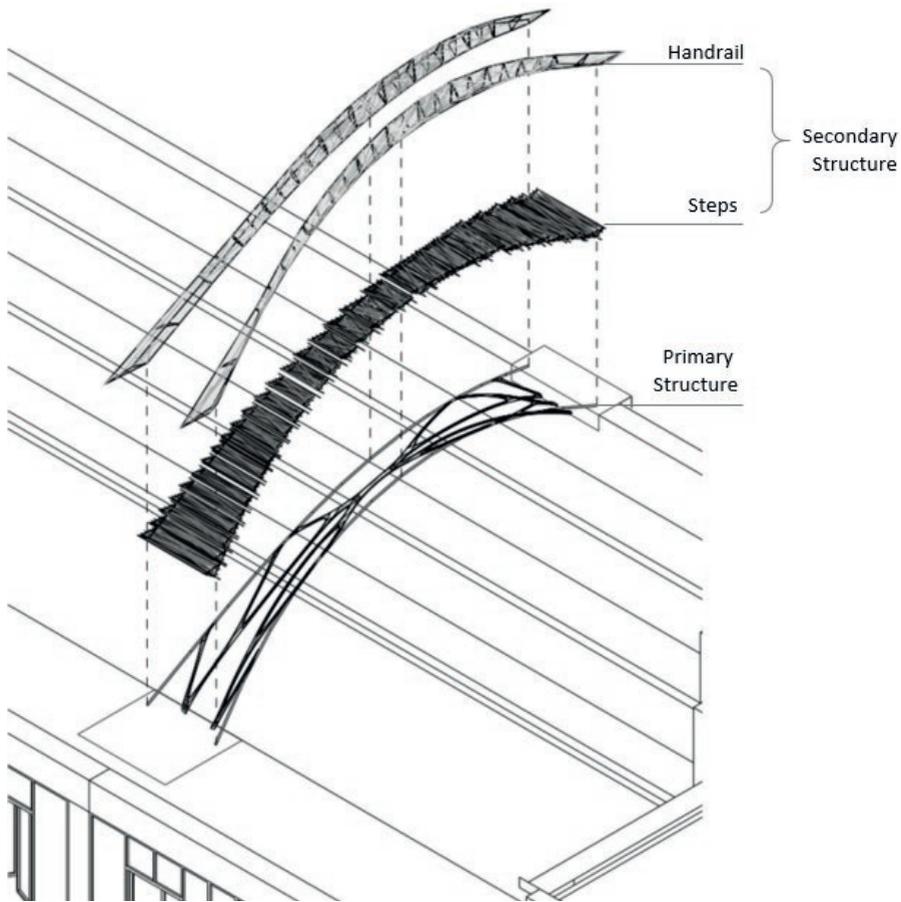


Figure 3. Three structural components of Hybrid Bridge

fabrication strategies.

A hybridized approach performs a higher complexity in the whole system, for it involved the integration of multiple fabrication strategies and material properties. As the project is a part of the DigitalFUTURES summer workshop, it has to pursue the timeline of completing the built project within seven days. Working around this tight schedule and by the effort of a small team comprised of only six members, the group designed a schedule where the design process and fabrication process will each take place 20 days before the

workshop begins, and allocating seven days for installation. As the overall workflow process has been presented by Li. W. et al. in [3], this paper will emphasize describing the details of the design process, as outlined in the next few sections.

Design Strategies, Methods and Processes

The exploded axonometric diagram (Figure 3) illustrated the three main components that made up the bridge's whole structure. The first layer from the



Figure 4. Form finding process through live physics engine

bottom is the metal 3D printed structure, which acts as the primary structure that carries the most load for the bridge. The second layer and third layer were staircase steps component and handrail component, respectively. Handrails and staircase steps are both considered the secondary components of the bridge and were designed using fiber filament winding technique, a novel production technology being used in developing building components in recent years within the architecture construction field. Metal 3D printing and fiber filament winding constituted the two main fabrication techniques in making this lightweight hybrid bridge.

Primary Structure Design

The primary structure of the hybrid bridge was designed to support the dead load from the structure itself and secondary components (handrails and staircase steps) and live load from the walking pedestrians. The first step of designing the primary structure was to define a basic arch geometry that spans according to the site dimension and determine the width of the bridge in order to produce a basic form for the pedestrian bridge. The bridge's model was brought in to live physics engine to be evaluated through interactive simulation and form-finding (Figure 4). At this stage, the bridge was undergoing several steps of iterations to produce the most ideal initial geometry under control of several parameters.

The resulting geometry was a relaxed plan that shows an approximation of the bridge's form with a skinnier waist in the middle (middle diagram in Figure 4). This initial geometry was then converted into a volumetric structural model that could be defined as boundary conditions for the topology optimization process

(Figure 5). The optimization algorithm undergoes a few iterations until obtaining the most lightweight and performative structure form possible.

The result of the topology optimization iterations became the most optimal model that defined the bridge prime structural geometry. In order to convert the geometry into a more refined geometry that complies with 3D metal fabrication conditions, the geometry output was again handed to undergo multiple objective optimization (Figure 6). The following objectives are set to be the parameter ranges that control the geometry output: (i) frame preliminary fitting, (ii) resistance to plane deformation, (iii) resistance to medial deformation, (iv) printing angle optimization, (v) façade connection optimization, (vi) construction joints optimization (Figure c). After this phase, the resulted geometry was a model that was ready to be manufactured by 3d metal printing, specifically the wire-arc additive manufacturing (WAAM).

Secondary Structure Design

The secondary structure consists of handrail components and staircase-step components that are fabricated separately from the primary structural structure. These two components were designed not primarily to carry the load but also to provide the pedestrians' stepping and hand-holding surface. In fact, it was constituted as a secondary dead load for the primary structure. Hence, the form and weight were determined to be a lightweight structure to reduce the total load. This consideration, together with some early research by ICDITKE Research Pavilion [4,5,6,7,8] on fiber-reinforced polymer (FRP) being used as experimental building components, has provided

整体结构拓扑优化 Global Structural Topology Optimization

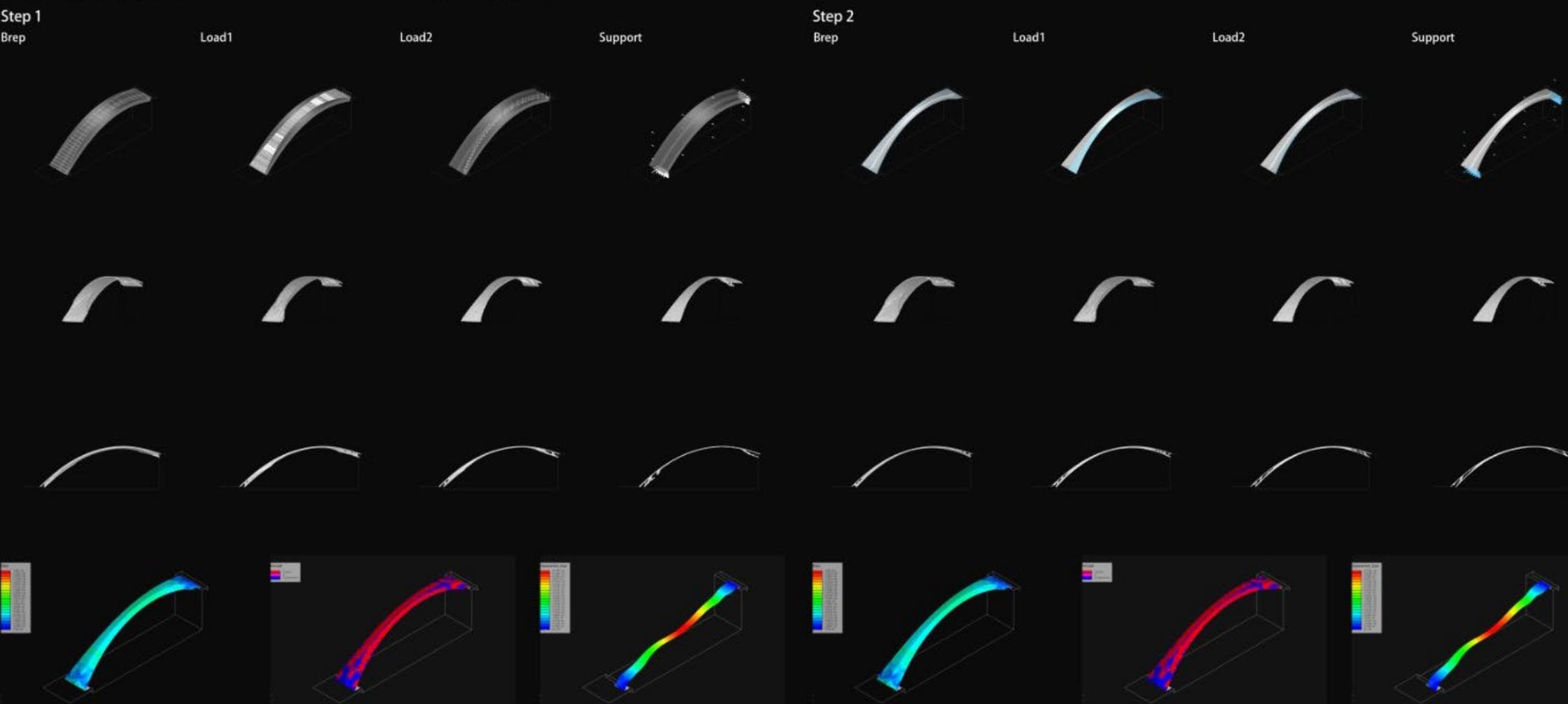


Figure 5. Topology optimization process of the bridge structure

a method to design by using filament fiber winding system.

FRP is considered as a modern material that could potentially become an alternate material to traditional building material such as metal for it has an over 10 times higher structural strength than steel. For example, carbon fiber (CFRP) has a strength of $\sim 780\text{kNm/kg}$, higher than that of steel which has $\sim 45\text{kNm/kg}$ [7]. It's high strength to weight ratio is an ideal property for project of lightweight structure, which make it highly suitable for the secondary component of this presented work.

The fiber winding system requires a geometry boundary that provides a winding point location to carry out the winding process. The first step in designing the secondary structure component was to determine the handrail frame and steps. While the form was negotiated parametrically in 3d modeling software, the size and the form of each component were also determined by other factors such as spacing between the winding anchor and minimum working gap size for robot winding end effector. The output metric from this was the winding frame, which was ready to be handed to a structural stress line simulation process that was subjected to load and structural optimization.

The arrangement of the fiber filaments was informed and derived by generated stress lines, which later on were converted to the robot winding pathway through a line simplification algorithm. The stress lines to robot winding path conversion was a process of stress lines simplification through joining neighboring stress lines to render a readable and fabricatable robot winding path. (Figure 7, 8, 9) presented the process of stress lines being converted to the winding path of each bridge steps and bridge handrails. The red lines represent tension lines that were wound by carbon fiber, while the blue lines represent compression lines that were wound by glass fibers.

Finite Element Analysis

To successfully ensure the safety of the bridge geometry, it was necessary to undergo a final detailed

structural analysis to simulate the load distribution and detect possible buckling region in the bridge design.

Two result models from each primary and secondary structure were used to run through a final analysis using Finite Element Analysis (FEA) to determine the load condition under different scenarios. An example shown in (Figure 10) exemplifies the stress map of the primary structure under full-bridge live load condition, and the half-bridge live load condition (Figure 11) shows the step stress analysis under different degree of stepping load condition. Taking the feedback from this analysis, the geometry design and fiber filament arrangement was continuously being iterated to achieve the most structurally stable bridge design.

Assembling Process Design

During design and planning process, the bridge (primary and secondary structure) was divided into 13 sections in consideration of factors such as limited-reach of robotic arm and to ease logistics process and assembling process (Figure 12). The installation process was divided into 2 phases. For off-site installation, 13 fabrication components were further welded into three assembly parts. All steps components and the middle section of handrail components were assembled onto the primary structural base, leaving the left and the right sections handrail components to be installed on-site later on. For on-site installation, two metal plates are placed on the ground at both ends to act as the foundation for the bridge in order to minimize any permanent damage made to the ground. Then, the three pre-installed parts are to be welded on-site and lifted by a crane to be placed into the designated location. The remaining uninstalled handrail on the right and the left side is the last step to complete the bridge installation. A load experiment shows that the bridge is estimated to be able to support a live load of about at least 20 adults. (Figure 13)

Conclusion and Future Research

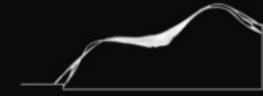
Furthered the bridge research project from previous DigitalFUTURES workshop in 2017 and 2018, the

多目标优化 Multi-Objective Optimization

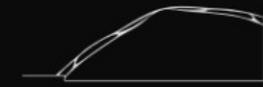
Frame Preliminary Fitting



Resistance to Plane Deformation



Frame Weight Loss - Resistance to Medial Deformation



Printing Angle Optimization



Facade Connection Optimization



Construction Joint Optimization

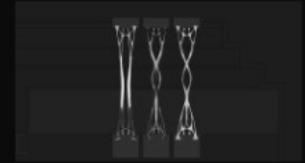


Figure 6. Multi-objective optimization process to generate a fabricatable geometry by 3D metal printing

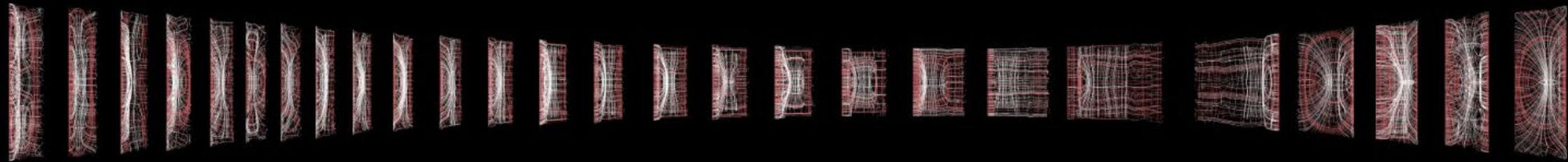


Figure 7.13 bridge steps fabrication components

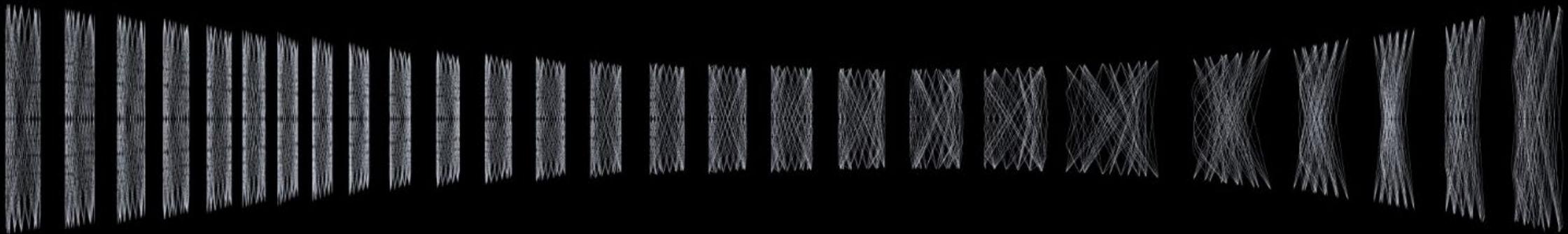
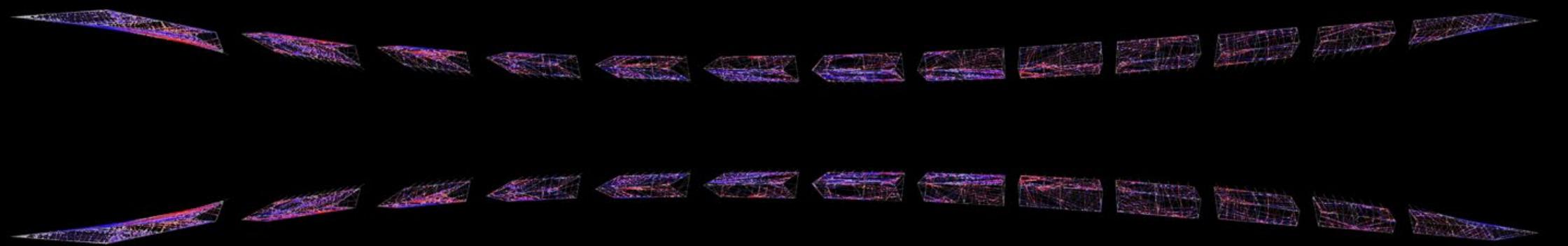


Figure 8.13 pairs of bridge handrails fabrication components



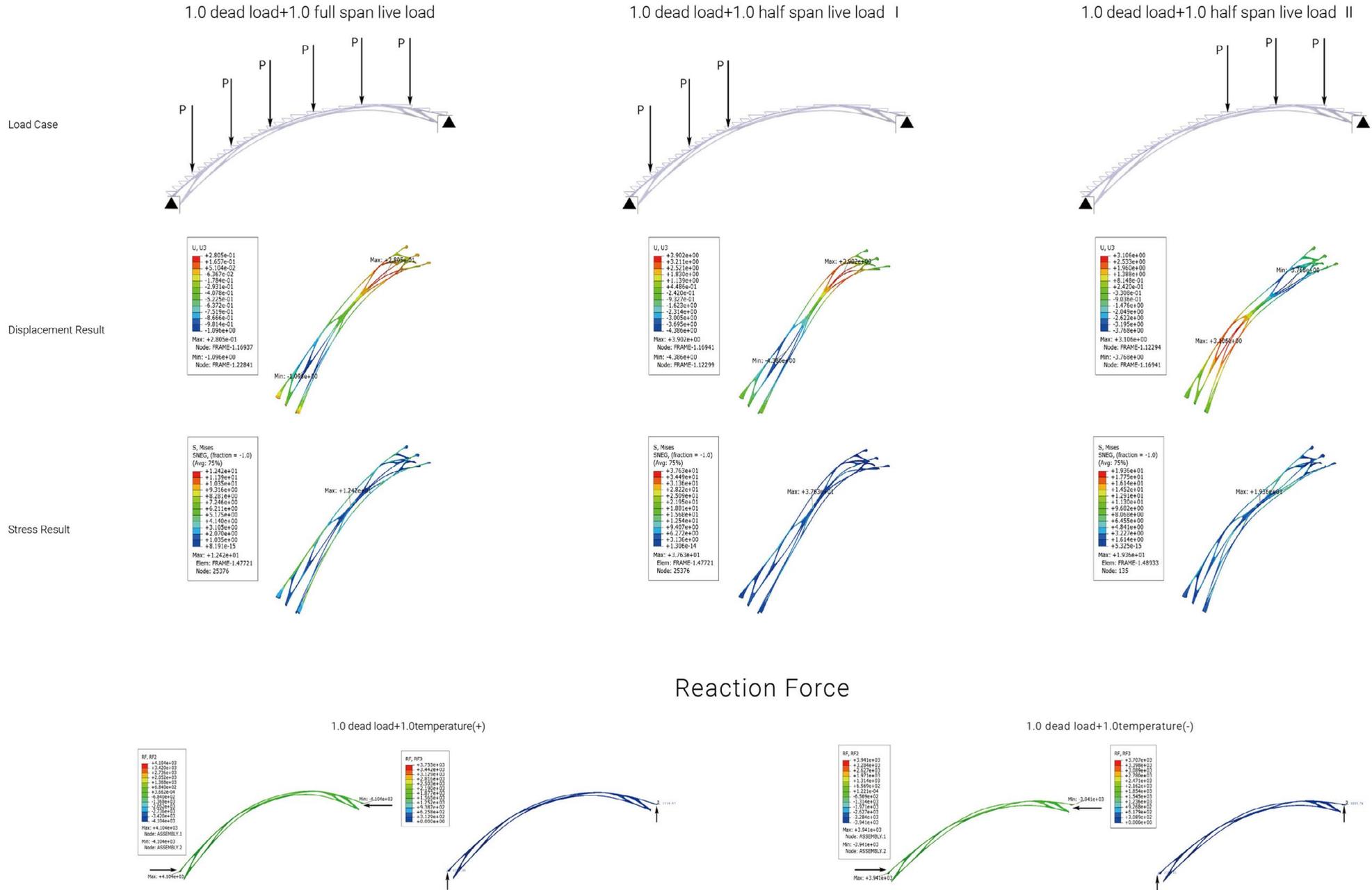


Figure 10. FEA analysis for live load distribution

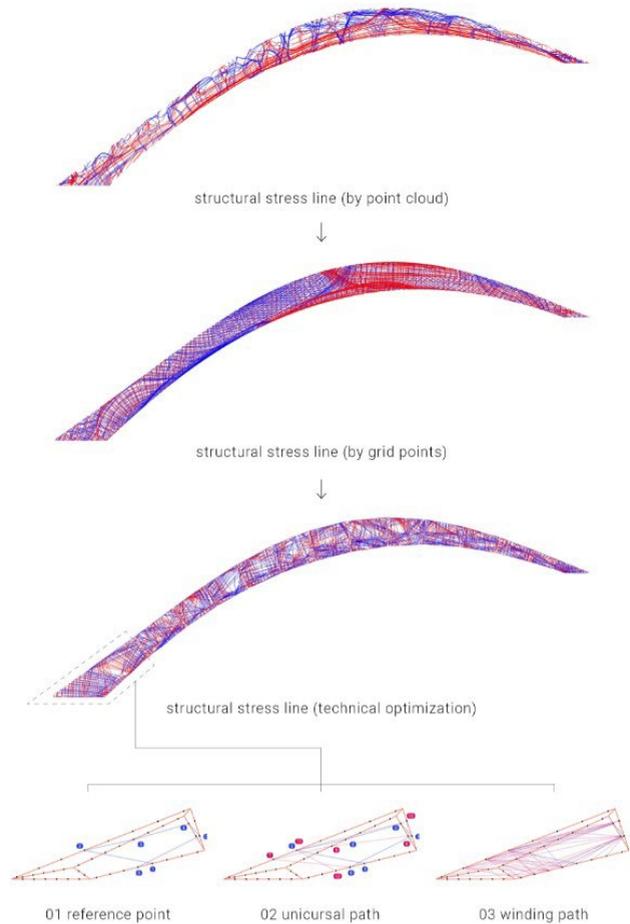


Figure 9. Structural stress line analysis

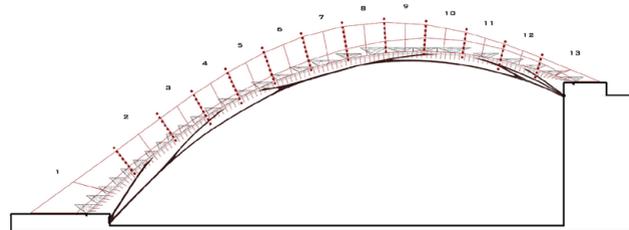


Figure 12. The bridge is divided into 13 fabrication components

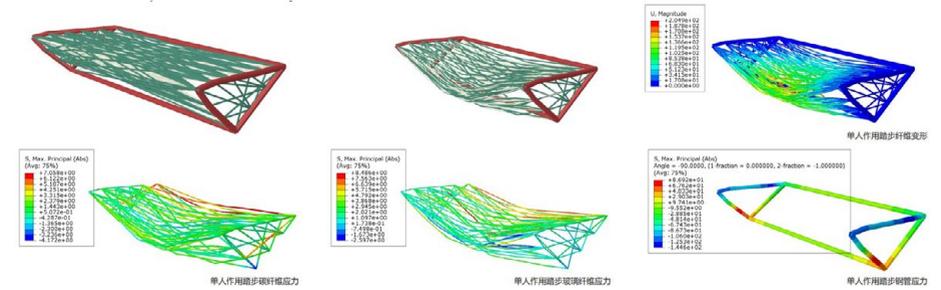


Figure 11. FEA analysis for live load distribution

presented work demonstrated the design process of a hybridized approach towards materials and fabrication systems that could be used to create a lightweight and performative bridge structure. Such hybridization approach is proven successful achieving structural integrity (bridge structure remained strongly intact after being fully occupied by standing and walking people as shown in Figure 13) with a minimum amount of materials used as described in the last section of paper by Li, W. et al. [3].

The design process of the hybrid bridge comprised of two phases. The primary structure is a 3D printed metal structure that was generated through live physics engine and topology optimization algorithms, while the secondary structure is a parametrically designed steel frame plus FRP winding structure that were accomplished through structural stress line analysis and line simplification algorithms. The FRP's high strength to weight ratio material property has introduced new structural possibilities and enables the creation of lightweight bridge component.

Influenced by fabrication materials and component's joinery designs, the fabrication component was divided into three parts, this strategy provided advantage for fast-paced project as the fabrication of each components can be done concurrently by several robots and later assembled on site. The challenge for this heterogeneous materials structure lies in joinery design between different components. For this project,

the steel joineries between the three components were designed and adjusted parametrically to ensure each components have extended anchors to be hand welded to another component. Potential area of future research could be focused on the development of joinery between winding frame of secondary structure and the primary structure base. For both off-site and on-site installation, the joinery welding process could be more extensively automated and fabricated by robot. Another area of future research would be the hybridization approach of designing, such approach could be further experimented with a wider range of materials and different fabrication strategies to harness the full potential of material structurality and to explore the compatible elements between different systems.



Figure 13. Load experiment after completion of project

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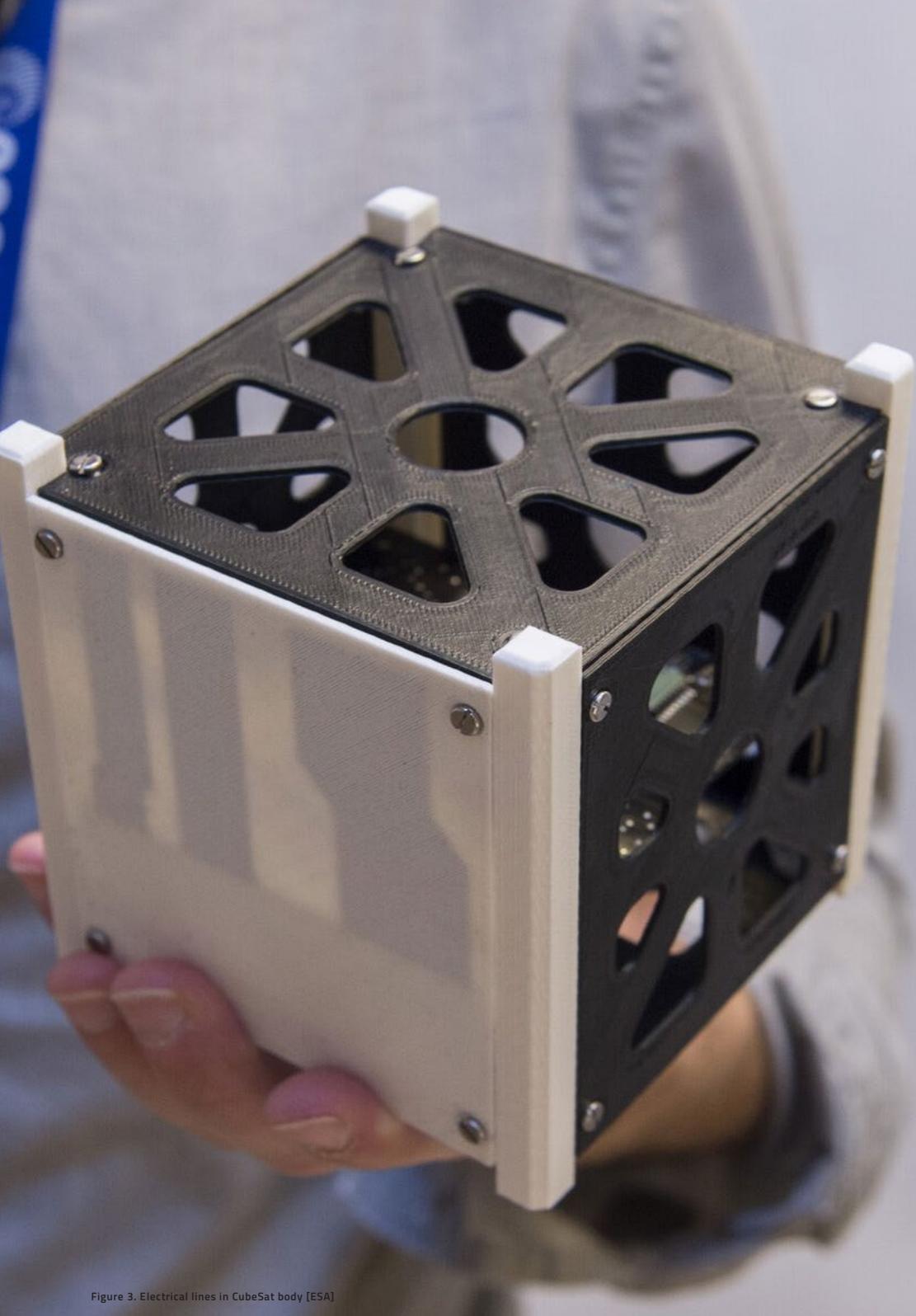


Figure 3. Electrical lines in CubeSat body [ESA]

3D PRINTING IN AND FOR SPACE

CHIARA MANFLETTI
EUROPEAN SPACE AGENCY
CHIARA.MANFLETTI@ESA.INT

Abstract

This paper gives a very brief overview of the use of advanced manufacturing methods, commonly known as 3D printing, in space, as well as the benefits it can bring for production of space components. A few examples, of the developments in Europe are given for different applications. For space, 3D printing in fact does not only mean that the design of components and systems can be rethought to better fit the function that needs to be fulfilled, or that production is possible of components and systems that would with conventional methods be otherwise complex or impossible to produce. Such advanced manufacturing methods open much farther-reaching possibilities such as the production of such systems in space for orbital, deep-space or planetary purposes. The challenges are still many. Additional thought should also be given to the sustainability of space activities in view of addressing both debris management, as well as recycling.

Introduction

The design of space systems results from requirements derived from the environment in which they are to operate and the need to transport these systems into space. As spacecraft move through space, they are exposed to solar irradiance, to solar and cosmic radiation, to vacuum, as well as to “deep

space” conditions, meaning that among other things, temperature gradients can be quite steep. Equally demanding are the conditions space systems are exposed to, when launched into space. Systems and components can be classified as access to space, in-space or as planetary.

Access to space system are launchers. Although we cannot speak of a real market for launchers, as most payloads are not accessible (as they would be under real open market conditions), their requirements are to be as cost-effective as possible to offer competitive prices and to provide mechanical, thermal, vibration, and acoustic environments which are payload-friendly. The Tsiolkovsky equation, also known as the rocket equation, defines the relationship between the initial and final mass of a propelled vehicle or spacecraft, based on the delta-velocity the spacecraft or vehicle is to have at the end of propelled flight. The equation shows that to maximise the delta-velocity imparted, the structural mass of the vehicle should be minimised. Building structurally optimised vehicles is a priority in the space sector. This results in staged launcher systems, whereby once a structure is no longer needed, e.g. a tank emptied of its propellant, it is disposed of. This is a requirement however which is sometimes in juxtaposition to security margins imposed. As advanced manufacturing methods allow to (i) design for use, rather than for manufacturing



Figure 1. The 3D printed M10 thrust chamber undergoing testing [ESA/NASA]

and assembly, as well as to (ii) produce components that could not be produced as single components and thereby reducing the complexity of manufacturing and assembly they provide advantages for a number of systems in a launcher. Many developments have been made with special attention paid to launcher engines and engine components, due to their complexity and due to their significant contribution to the total cost of a launch vehicle. Examples are provided in the next sections.

In-space systems are spacecraft which remain in orbit or in space during their entire functional life. The design challenge of these systems is to perform all necessary functions in a volume which is as small as possible, a structure as light as possible and with power consumptions which are as small as possible whilst not violating required thermal operational conditions of each component installed in the spacecraft.

Miniaturisation is one of the most significant trends linked again to the pressure to reduce the cost of access to space and space-data, also referred to commonly as democratisation of space.

Planetary systems are spacecraft which are intended for use on other bodies, such as the Moon, Mars, Jupiter or a Comet. Like for in-orbit systems, the design challenge is to build as lightweight and compact as possible. Beyond the launching phase, the most challenging requirements are associated with the descent on and entry into the atmosphere of these planetary bodies and thermal day/night gradients.

Some challenges could be overcome by manufacturing such systems at the location where they are needed, also known as in-situ resource utilisation (ISRU) and in-space manufacturing. Mastering the properties of in-situ resources, such as lunar and Martian soils or asteroid materials, and possessing

the right methods and systems for manufacturing are critical. Steps beyond in-space manufacturing and towards in-space recycling should also be taken. Indeed, sustainability aspects (economic and environmental) should not be neglected and considering them from the beginning will help direct activities.

There are more than 750 000 pieces of debris in orbit with a size larger than 1 cm, which can all become potentially mission-ending. Of the 4500 satellites that are currently in orbit, only 1500 are active. Daily collision avoidance manoeuvres are required to avoid catastrophic events from happening, which can result in cascading effects. ESA receives a few hundred collision alerts in a day for its fleet, with a single collision event in 2009 having doubled ESA's avoidance efforts. There is one major uncontrolled re-entry event every week amounting to 100t in a year.

3D Printing and Examples

Some of the early work was associated with rapid prototyping. 3D printing of using plastics was and is still used for design purposes. This was followed by metals and ceramics. Some of the methods used include powder bed fusion and direct metal deposition, selective laser sintering, stereo-lithography, and fused deposition modelling. The ability to combine different materials and therefore to reduce the number of individual parts to be produced is desirable.

Access to Space

One of the more recent developments in European access to space includes the testing of the 3D-printed thrust chamber assembly of the methane-fueled M10 rocket engine. This liquid rocket engine is to power

the upper state of a future evolution of the European Vega launcher. The 3D-printed thrust chamber passed its first series of hot-firing tests in February 2020 (Figure 1) with the aim of launch in 2025. Thanks to 3D printing, the M10 engine is expected to be cheaper to manufacture, as well as more environmentally friendly than currently used propulsion systems.

Liquid rocket combustion chambers of high pressure engines generally consist of an inner copper alloy structure, which has cooling channels for heat transfer purposes and an outer nickel structure for pressure and loading carrying purposes. The ability to 3D print parts consisting of different metals is therefore very important.

Other examples of components in propulsion systems of launchers include injector heads and injection elements. These are complex, consisting of many sub elements and traditionally hand assembled. 3D printing these components allows to simplify the overall system. Surface roughness and resulting pressure losses are some of the concerns when moving more machined parts to 3D printing. Extensive testing has shown that these differences can be mastered.

The current micro-launcher whereby start-ups compete to bringing low-cost access to space services for payloads below 500 kg has also triggered a stronger development of 3D printing for more complex parts such as turbopumps, something which so far had been investigating into by larger companies and public sector players.

The above examples complement other 3D printing developments in structural elements used across the launcher and its stages.

	Sun	Earth	Moon	Mercury	Venus	Mars	Jupiter
Gravitation	274 m/s ²	9,8 m/s ²	1,6 m/s ²	3,7 m/s ²	8,9 m/s ²	3,7 m/s ²	24,8 m/s ²
Surface temperature	5504 °C	-89 °C	-160 °C	-173 °C	+437 °C	-143 °C	-108 °C
average temperature of the photosphere		+ 57 °C	+130 °C	+427 °C	+497 °C	+35 °C	

Table 1: Gravitation and surface temperature for the Sun and solar system planetary bodies

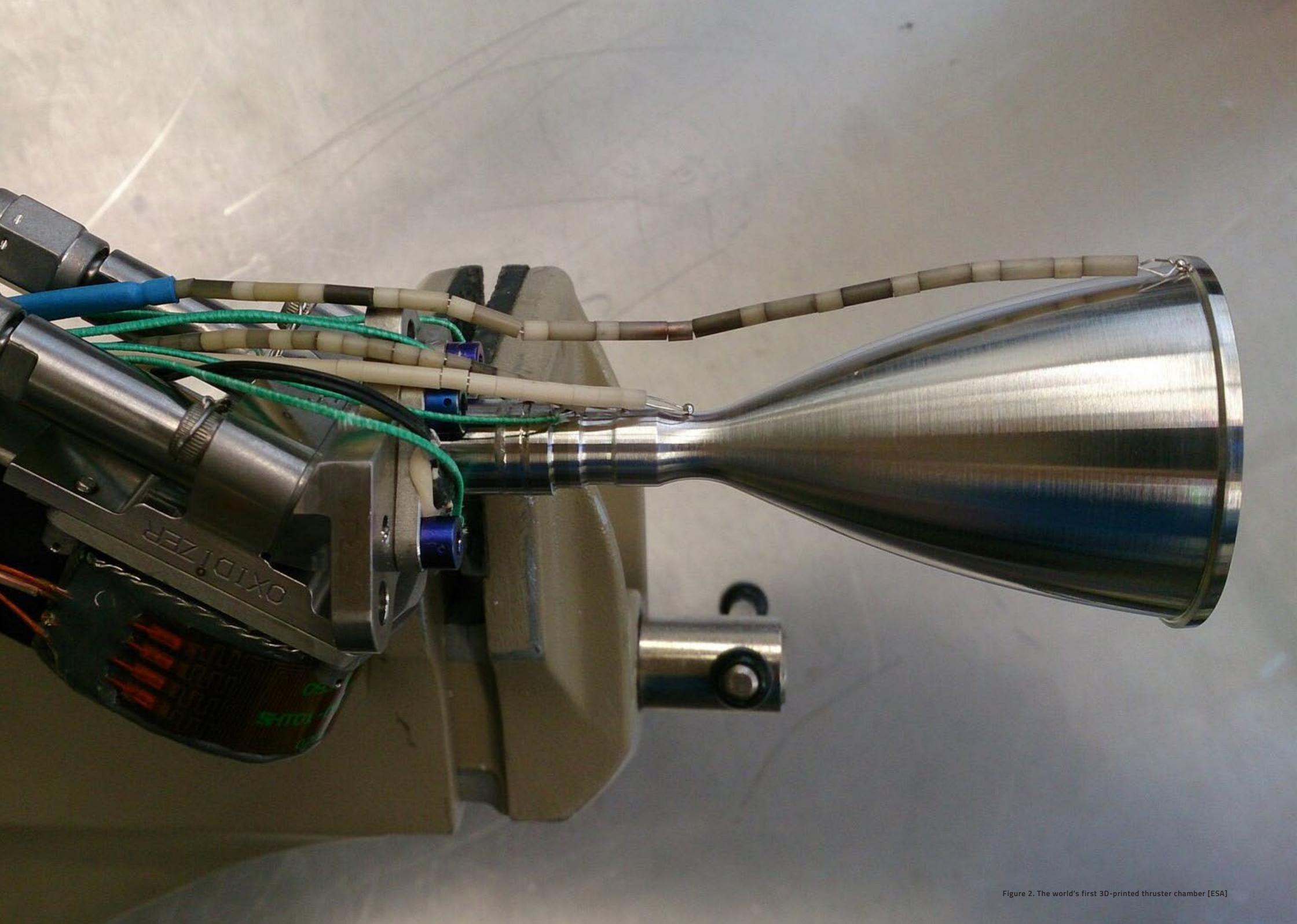


Figure 2. The world's first 3D-printed thruster chamber [ESA]



Figure 4. 1.5 tonne building block produced as a demonstration [ESA]



Figure 5. Artist's views of a multi-dome structure [ESA]

In-Orbit System

The world's first spacecraft thruster, as depicted in Figure 2, with a platinum combustion chamber and nozzle made by 3D printing passed its baptism of fire with a series of firings lasting more than an hour and 618 ignitions in 2015. The firings included a single burn of 32 minutes, during which a maximum throat temperature of 1253°C was attained. The project was implemented by Airbus through the European Space Agency, ESA.

Other developments examined the possibility of creating more compact and integrated systems. One of the first test was that of a new printable hard, electrically conductive plastic with the purpose of obtaining 3D-printed CubeSat structures incorporating their own electrical lines as depicted in Figure 3.

In-Situ Resource Utilisation and In-Orbit Manufacturing

For sustainable exploration activities, the use of in-situ resources has been investigated into for many years

now. Early work with 3D printing investigated into the feasibility of using lunar soil for building of habitats and other structures. Figure 4 depicts a demonstrator printed to this purpose, where the cellular structure, providing a good combination of weight and strength – would be part of a weight-bearing 'catenary' dome wall designed to shield against micrometeoroids and space radiation and which would cover a pressurised inflatable to shelter for astronauts (Figure 5).

Research work done in the field of in-space manufacturing has commenced by looking into the production of simple tools for astronauts on-board the International Space Station, ISS, with 3D printers tested in zero-g flights and on the ISS, where activities are not limited to manufacturing of metals and polymers and ceramics, but also include food and biological cells.

Manufacturing in-space in zero or low-g environments comes with special boundary conditions. The absence of gravitational effects means, for example, that temperature differences in a fluid do not produce

convection, buoyancy or sedimentation. In weightlessness, sedimentation and buoyancy-induced flows are virtually eliminated and the possibility of measuring thermo-physical properties of materials (e.g. metals, foams, emulsions, high-quality crystals and high-performance alloys) under such conditions may lead to high accuracy in the analysis of the underlying processes.

For manufacturing processes when not subjected to strong gravitational forces, proteins, materials and other elements can crystallise without external constraints thus allowing for purer, uniform products that have enhanced properties, which is especially interesting for a number of materials but also for other purposes such as pharmaceutical purposes.



ADVANCES IN 3D PRINTED EARTH ARCHITECTURE: ON-SITE PROTOTYPING WITH LOCAL MATERIALS

ALEXANDER CURTH*, BARRAK DARWEESH, LOGMAN ARJA, RONALD RAEI
MIT SCHOOL OF ARCHITECTURE + PLANNING / UNIVERSITY OF CALIFORNIA
BERKELEY COLLEGE OF ENVIRONMENTAL DESIGN
CURTH@MIT.EDU

Abstract

Recent advances in large scale 3D printing hardware and software have made on-site additive manufacturing possible with locally sourced materials. By calibrating a robust pump system to different combinations of sand, clay and straw, earthen structures can be 3D printed in sections of up to 60 cm a day. Leveraging local material knowledge and traditional mixing techniques, mud mixtures of comparable compressive strength to conventional mudbrick construction can be formulated without the need for synthetic additives. To bridge the gap between the geometric freedom of desktop scale FDM (Fused Deposition Modeling) printing and the limitations of slow drying earthen materials new methods of angled deposition, progressive layer height and multiposition printing are proposed and tested.

Introduction

For 10,000 years people from nearly every region of the world have built structures made of earth [1]. Today over three billion people live and work in buildings made from local soil [2]. While earthen walls are commonplace, roof structures that are made of earth are less so. Many examples of earthen architecture employ wood beams that span across load bearing walls to support ceilings and roofs. However, regions that lack timber have developed more creative methods of roof

construction using earth alone by employing vault and dome structures. While many techniques for vault and dome construction require shuttering, often also made of wood, there exist several techniques that require no shuttering at all. For example, the Persian Ctesiphon Palace, built fourteen centuries ago, used only simple mud brick to span over 25 meters without the need for formwork during its construction. While recent examples of large scale additive manufacturing for architecture are limited to the construction of walls and layer deposition parallel to the ground plane, still often using timber structures as roofs, ancient technologies hold great promise for creating roof enclosures using additive manufacturing methods translated from traditional earthen masonry construction. To explore this potential, a framework has been developed for additively manufactured earth roof structures that utilizes ancient brick laying strategies to arrive at structurally stable vaults and domes.

This paper documents the application of ancient structural principles using computer aided design, simulation, and additive construction tools. We present examples of 3D printed earthen wall structures fabricated and conclude with the examination of a range of our recent experiments in developing toolpaths and algorithms for additively manufacturing structural earthen vaults and domes that can be constructed



Figure 1. A ceramic vault 3D printed without formwork.

on site without the use of shuttering or formwork. In addition to adopting vernacular construction techniques from North Africa and the Middle East, we reference late 20th century theories by additive manufacturing pioneer Behrokh Khoshnevis [3], who speculated on 3D printed vault structures. Our material palette utilizes traditional soil mixtures, a masonry pump, portable low-cost tools, and a robust, lightweight, SCARA robotic arm developed with an industry partner.

Methods

An often-noted advantage of additive manufacturing is the ability to increase design complexity at multiple

scales without large increases in production time or cost. To better manage broad spans, custom software tools have been developed to manipulate layer height (progressive layer height), and generate angled, interlocking toolpaths for the production of vaulted constructions without a need for formwork.

Printing Procedure

Small scale (1:50) tests referenced in this paper utilize a 3-axis cartesian style 3D printer [4]. The workflow begins by filling tubular cartridges with de-aired clay processed in a pugmill. The cartridges are then mounted onto an end effector which moves the



Figure 3. Vault printing at 1:10 with a 3-axis printer.

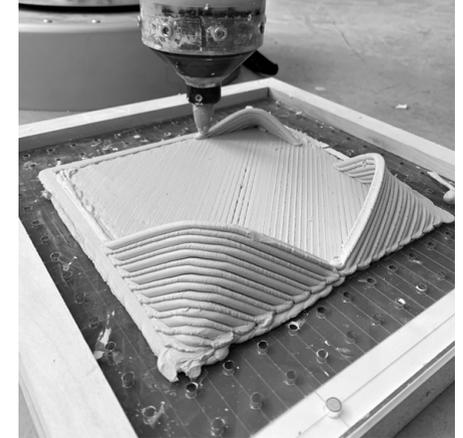


Figure 3.1.

tube of clay within a designed, high precision toolpath. A motorized piston pushes clay through the mounted tube into a 4mm nozzle. 3D printed objects are typically sliced and extruded in a horizontal layered fashion, due to the nature of the material extrusion and availability of slicing software. Our approach to manufacturing dome and vault structures follows a nonplanar, angled slicing configuration which mimics vernacular brick laying patterns.

Scaling to 1:10 and beyond, tests were conducted in adobe (see mixture information below), transported to the nozzle of a SCARA (Selective Compliance Assembly Robot Arm) printing robot through an auger driven stator pump. Like the smaller scale Cartesian system, the SCARA system has three degrees of freedom, however the onboard configuration software translates cartesian machine code (gcode) into polar coordinates to drive the arm's kinematics. Both machines are controlled through Wi Fi and a web interface that allows for real-time manipulation of printer speed.

The primary advantage of a SCARA type printing system over a Cartesian printing system is the allowance for the production of structures many times the size of the robot itself and is lightweight and portable. The robot used in these tests has a footprint of 0.5 meters and can print up to a three-meter diameter object. To further extend the reach of the mechanical system a 4th axis was constructed with three fixed printing positions

Material

For thousands of years, builders have used locally sourced soil to create adobe bricks, rammed earth walls, and cob for low cost construction. The tests shown in this paper makes use of both pure clay industrially produced and locally sourced materials which are comprised of clay, silt, and sand, with the addition of chopped straw and water. All earthen mixture components are screened to reduce maximum particle size to 2-3 mm. Straw fiber is reduced to a maximum length of 6cm. Typical building material for adobe or rammed earth construction has a clay content between 25% - 45% with a minimum compressive strength of 21 Kilograms Per Square Centimeter [5]. Higher clay content allows for a more plastic, easily extrudable material but also results in a higher shrinkage and cracking rates. Printing with the driest possible mix reduced both shrinkage and cracking but these advantages must be weighed against the increased wear on the consumable elements of the stator pump system.

Progressive layer height

To achieve earthen 3D printed forms with greater than a 3-5 degree vertical slope progressive layer height strategy was employed. As slope increases from base to top in a printed form, as in the case of a dome structure, progressively reducing layer height maintains an effective level of overlap between layers of deposited



Figure 4: 3D printed 1:50 ceramic vaults of varying slope, geometry, and interlocking toolpath strategies.

material. Progressive layer height reduction requires consideration of three variables: Maximum slope, extrusion width, and initial layer height. This strategy is most effective on funicular domes and vaults structures.

Angled deposition

Domes and vaults work within the same principles of compression and uniformly distributed loads to achieve structural efficiency through geometry [6]. Two types of brick structures are analyzed, the Nubian vault, and the squinch dome [7]. The squinch dome is built over a square plan. Starting at the four corners of a plan, bricks are laid in layers leaning towards the corners. As the bricklaying process is repeated, bricks lean gradually towards the center and naturally meet resting in compression. Vaults, on the other hand, are curved in a single direction. A wall with a curved cap (espar) is first constructed, making the back wall of the vault. Bricks are then layered at a 10-15 degree angle against the

espar to build up leaning courses of brick that support each subsequent layer with the majority of vertical loads being transferred diagonally through the espar wall.

Using a three axis cartesian paste extruding 3D printer, vaulted enclosures are printed in stoneware clay at a 1:50 scale (see Fig. 4). Early prototypes reconsidered the basic barrel vault by closing one end, which enables supported angled printing, much like the angular coursing of Nubian vaults that lean against an existing adobe wall. This minimizes unsupported overhanging elements and allows for a consistent flow of forces through the walls of the vault or dome. Test vaults were created with slopes of 15, 30, 46, and 60 degree angles. Reducing slope angle allows for fabrication with a three-axis robot but limits the span of a vault. Steeper angles are possible by using an angled extrusion nozzle or a robotic system with greater degrees of freedom to keep the print head oriented normal to the extrusion direction (see Fig. 3). Test vaults also included ellipsoidal or

dome-like termination to the barrel. These vault types successfully translate forces in compression, supporting the angled layers of the rest of the vault.

Interlocking toolpathing

Taking inspiration from the ingenious geometry of Guastavino's late 19th century structural tile vaults an interlocking toolpath logic is built into the toolpathing workflow to increase layer adhesion and overall stability [8]. Utilizing a similar gradated offset wave pattern perpendicular to the print head normal vector we can decrease wall thickness from the base of the vault to the crest thereby minimizing the use of material and limiting load on the vault itself. Additionally, this strategy eliminates the need for multishell/repetitive toolpaths aiming to selectively thicken a printed wall structure [9]. Printing duration is reduced while engaging what is perhaps a function-oriented textural aesthetic made possible only by direct toolpath control. These toolpaths

are reminiscent of Guastavino's herringbone tiling patterns, which are the product of rigorous structural intention while imparting an aesthetic component to the architecture.

Conclusion

While tests at small scale in pure clay are consistently successful, creating a full-scale earthen structure with an angled printing methodology presents several challenges. The authors have succeeded in printing base case prototypes of both a vault and dome at a 1:10 scale. To do so required a more conservative approach, which included printing at a lower feed rate with a carefully calibrated earthen mix, and minimal water content. The integration of gcode based toolpath manipulations for microscale improvements in layer adhesion, and control over wall section thickness has opened new doors. With these new advancements we see great potential for bridging the gap between our printed roof prototypes

and the full-scale walled structures we developed in previous projects. Recent full-scale prints successfully employ progressive layer height to achieve domed structures with steeper angles than previously possible.

While these approaches are widely adaptable to other robotic systems (six-axis arms or large scale cartesian gantry printers) and extruded materials (concrete, foam, bioplastic), we are particularly encouraged by our early results which only use earth, and a portable SCARA printing system. We believe that the size of the platform and the use of an abundant material, brings full-scale additive manufacturing to the reach of a wider range of users and applications.

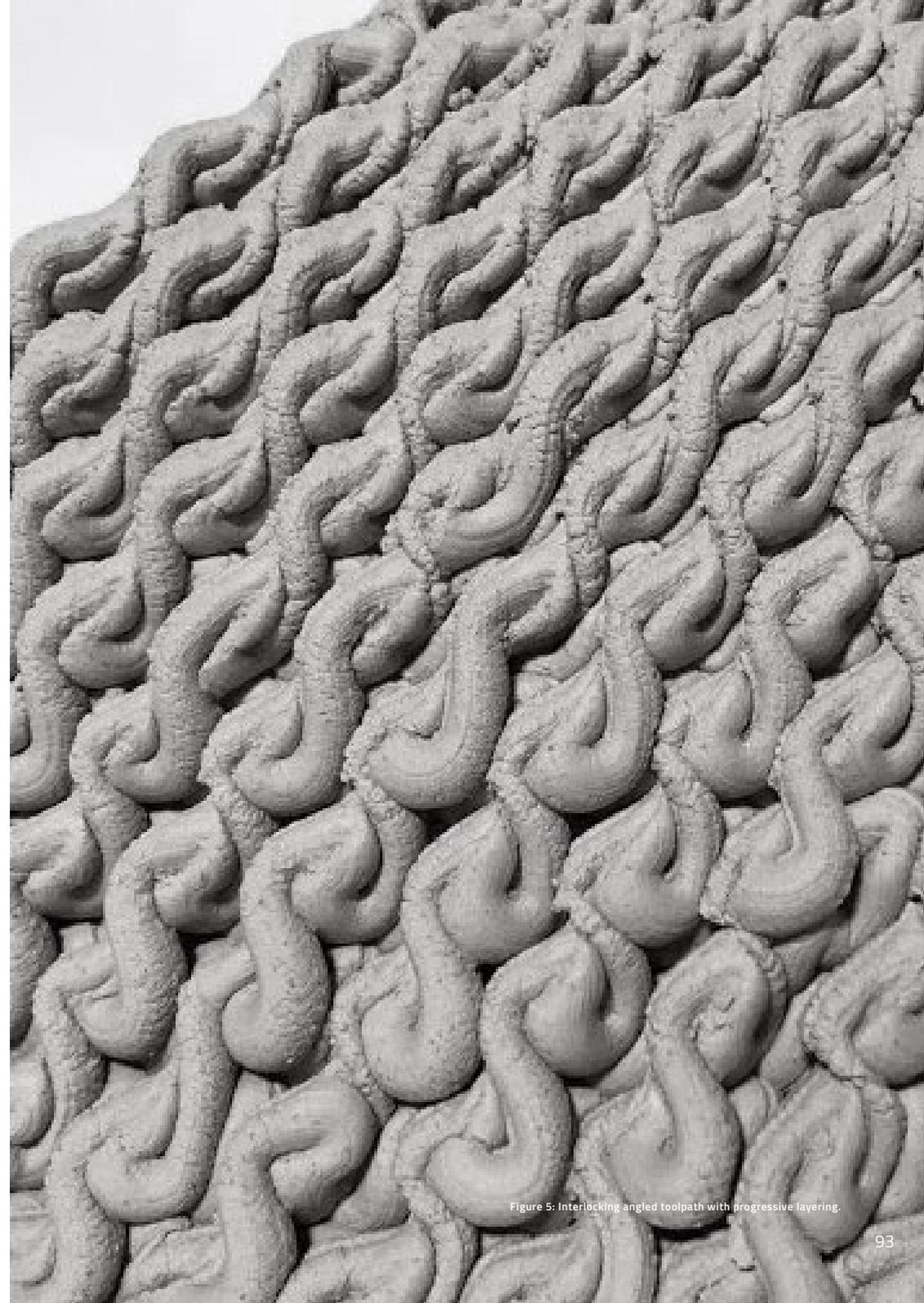


Figure 5: Interlocking angled toolpath with progressive layering.

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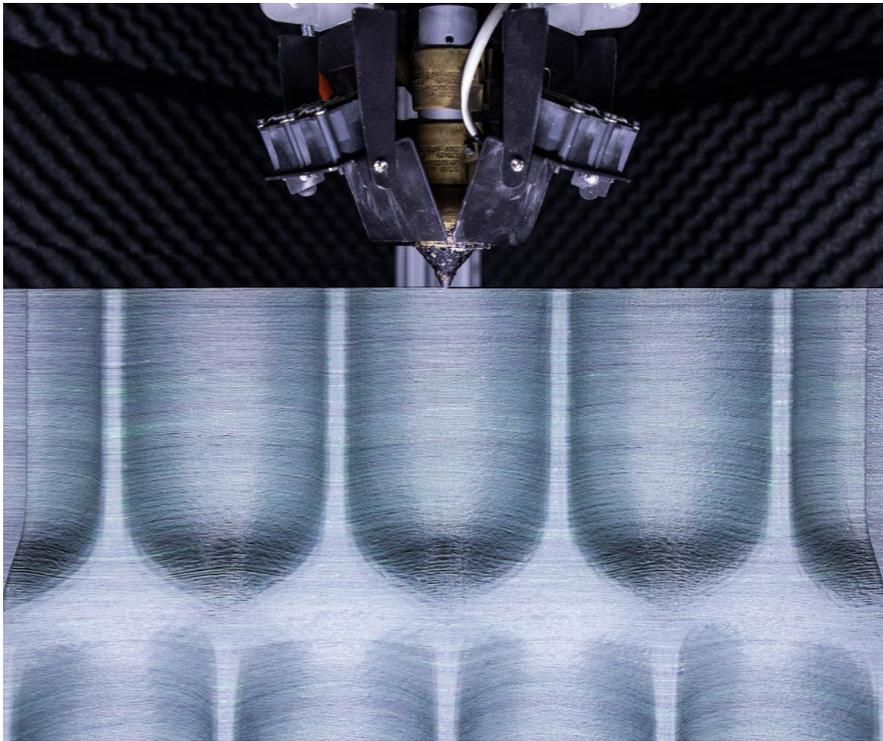


Figure 6. 3D printed tower

PROJECTS

HIGH-RESOLUTION CONCRETE PANELS WITH ADDITIVE FORMWORK

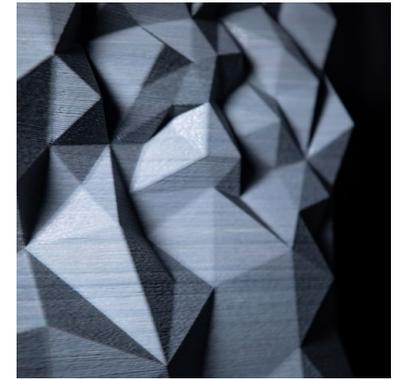
CREATE - University of Southern Denmark, ITI
Roberto Naboni, Luca Breseghello, David W. Joksziens
www.create-sdu.com



The project High-Resolution Concrete Panels with Additive Formwork seeks to untap the full potential of concrete by exploring a novel approach to formwork manufacturing. Through the combination of computational design logics and the flexibility of Additive Manufacturing, this experimental work exploits unreached levels of customization for the most used material in constructions.

The lack of detail in existing formworking confines concrete architecture to passively inherit the features of moulding materials such as wood. This work utilizes computational processes to actively characterize a further design dimension, the one of texturing, which is informed by performative and morphological features.

To celebrate the possibilities offered by the union of high-resolution 3D Printing and the material properties



of Ultra High-Performance Fiber Reinforced Concrete (UHPFRC), a set of concrete panels with unique design was realized, following distinct computational processes ranging from natural to abstract inspirations: from the organic shapes generated by reaction-diffusion logics, sphere packing, sand wave patterns, to polygonal assemblies that resemble mineral formations, meshed surfaces, and topological discontinuity.

The fabrication process involves the use of large scale Fused Deposition Modelling (FDM) and upcycled plastic waste to shape additively formworks that have highly unique morphological features: multi-scale curvature, variable sections, topological discontinuity, sharp/smooth edges. High-precision 3D scanning has been utilized to evaluate the precision and repeatability, with average deviations smaller than 2 millimeters.

Ultimately, the project demonstrates the unique possibilities of producing high-resolution and high-precision concrete panels for indoor and outdoor applications, with the use of reusable formwork made of upcycled plastic material.



PLASTIC TESSELLATED SURFACE

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Philip F. YUAN, Weizhe GAO, Liming, ZHANG
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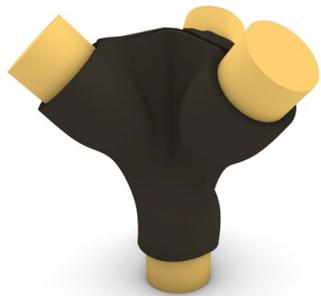


This work is a mock-up version of Happy Valley's Grande Gate project in Nanjing, China. In that project, the designer applied geometric topology in form finding process, integrated with the multi-colored mosaic pattern and redefined free-form geometries in spatial design. Implementing with three-dimensional printing technologies and robotic fabrication, the gate was finalized with over two thousand pre-fabricated panels on its surface. Meanwhile, every single panel was positioned accordingly with the laser tracking system. The application of three-dimensional printing technologies and precise positioning by using laser tracking tools has resulted in a highly qualified design.



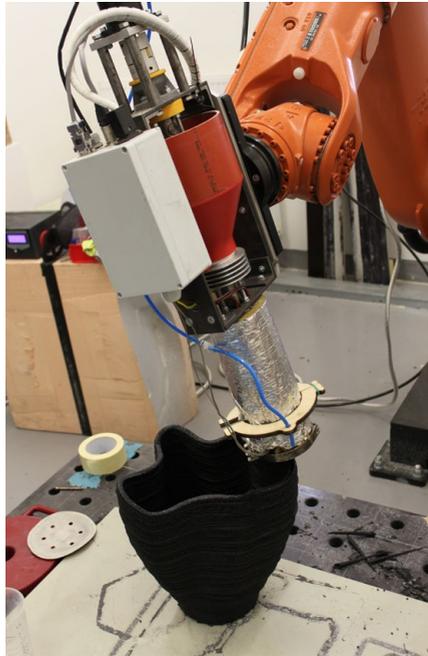
POLYBET

BUT, IMID
Martin Krčma, David Škaroupka, PhD.
www.3dlaboratory.cz



The submitted object is a one of a series of connecting pieces, enabling construction of a wooden beam structure, such as a patio or a pavilion. The beams are 10 cm in diameter. The intent of the design is to showcase material properties and possibilities of using it in the construction industry.

The object is manufactured from polymer concrete, made up of recycled, post-consumer plastic and aggregate (sand). The material has a working name - POLYBET. The main benefit of the material is its decent mechanical strength in tension compared to traditional



concrete combined with a low price point due to utilization of waste that would typically be burnt or landfilled.

The printer consists of a Kuka robot arm and screw extruder developed by our department in partnership with ViaAlta company. The prints are performed utilizing 5-axis nonplanar strategies planned in Grasshopper, which allow us to print large overhangs and achieve improved surface quality.

Submitted photos are of a showcase vase printed by the same technology and material, utilizing nonplanar, 5-axis strategies.



GREEN FACADE

Vertico

Volker Ruitinga, Karin van Beurden, Ivo Vrooijink, Iman Hadzhivelcheva, George de Witte

www.vertico.xyz



The Green Façade is the first 3d concrete printed structure in Twente realized by the cooperation between Saxion Industrial Design Research Group, De Witte van der Heijden Architecten, Vertico large scale 3D printing and Trebbe.

In 2016 Saxion Industrial Design Research with head lector Karin van Beurden initiated a 2 year research project on 3D concrete printing RAAK KONKREET sponsored by SIA.

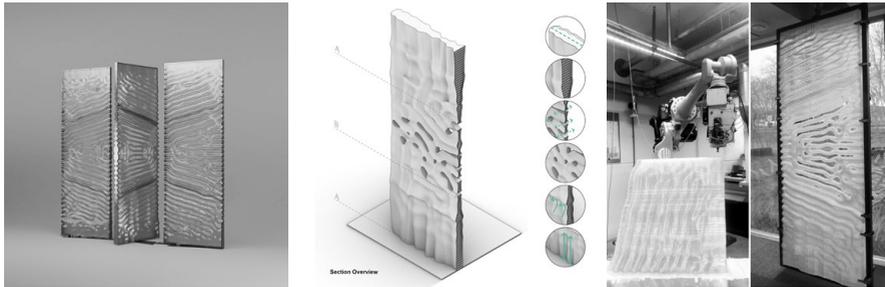
George de Witte from De Witte van der Heijden suggested that the structure be created for the interior garden of Stepping Stones' building realized by Trebbe. The basic design was developed by Iman Hadzhivalcheva under the project management of Ivo Vrooijink. The final design was made via parametric modelling in which each piece was made to have unique form, fit on a pallet for easier transportation and weight under 50 kg so the big structure can be built by stacking the pieces on top of each other by two people.

The 50 unique elements were printed using our large ABB robot arm and a gantry by Rohaco. The façade weights approximately 2,5 tons. The transport and installation was managed by Trebbe.



DOUBLE FACE 2.0

TU Delft, Architectural Engineering + Technology
Tudor Cosmatu, Stavroula Tsafou, Yvonne Watzet, Michela Turrin, Martin Tenpierik
<https://journals.open.tudelft.nl/spool/article/view/2090/2442>

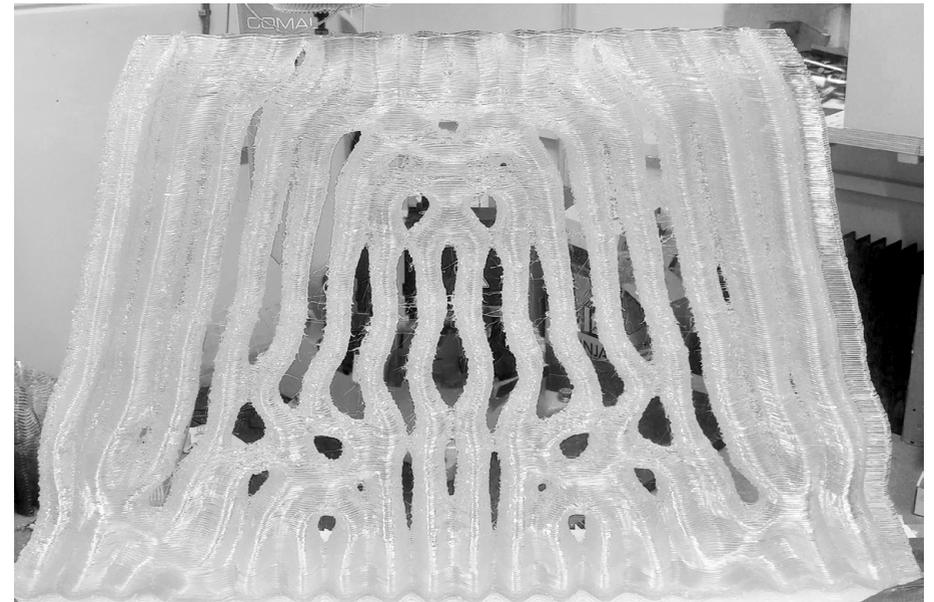
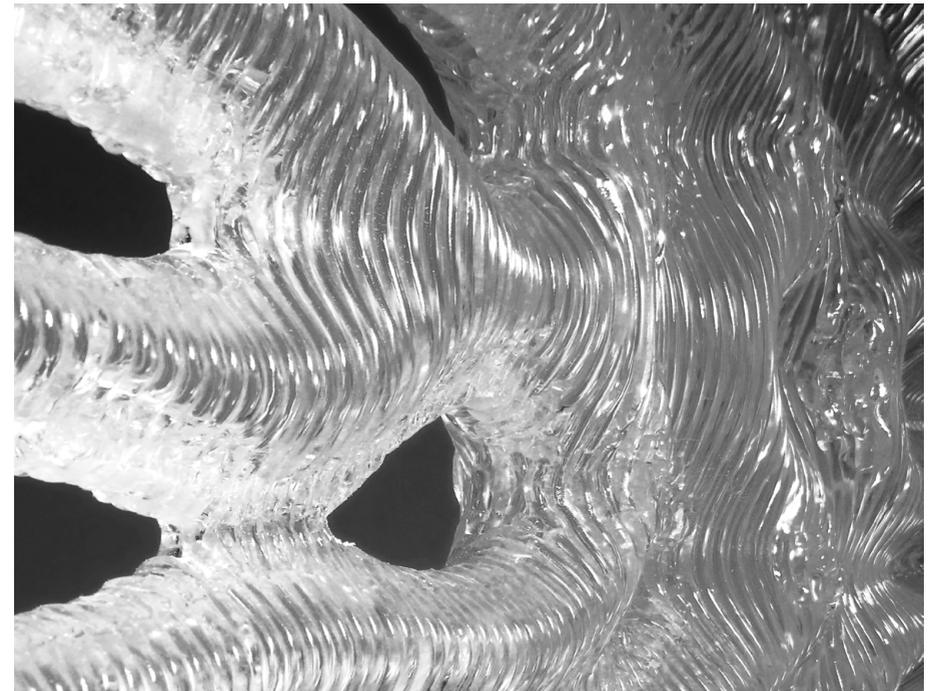


The Double Face 2.0 is a Research Through Design project (no. 14574), financed by NWO and SIA. It investigated a novel translucent solar wall using large-scale robotic additive manufacturing as a production method. The research through design driven approach involved the use of physical and computational models for measuring, exploring and iteratively improving the design.

The solar wall combines high-performing materials, such as phase change materials for thermal storage based on latent heat and aerogel for thermal insulation. The design problem addresses a container to be designed in a way that heating and cooling cycles are enhanced, while allowing visual connection and sufficient natural light to pass through. The design decisions are based on findings from building physics simulations regarding heating and cooling cycles, required minimum and maximum material thicknesses of the container and active materials, as well as structural

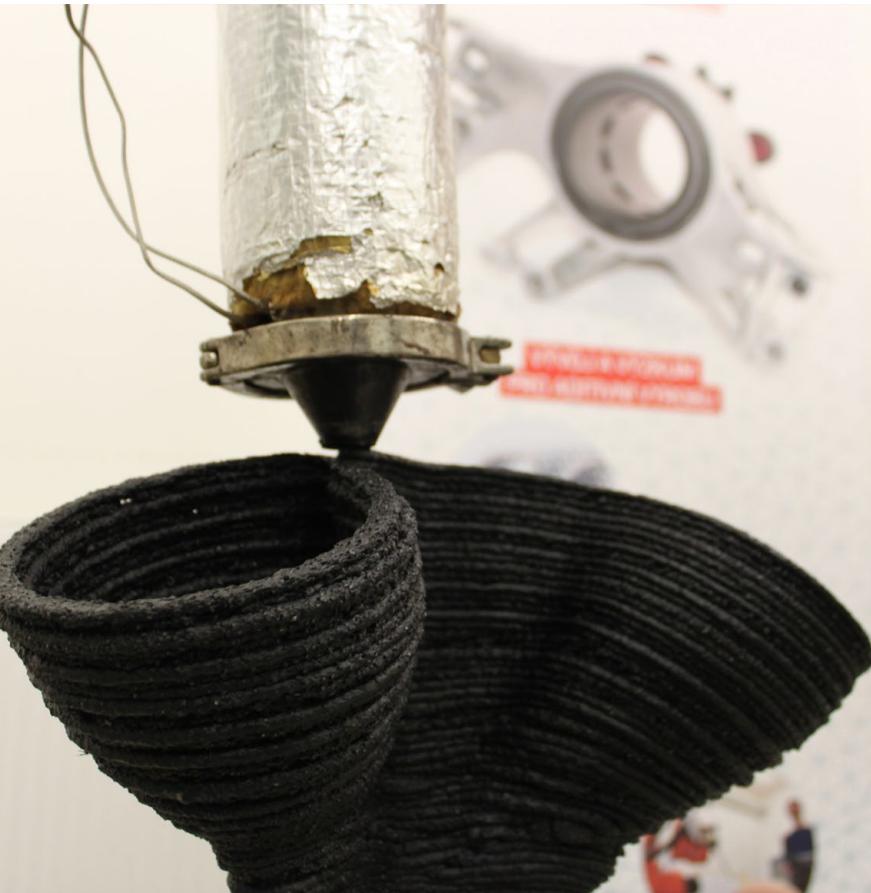
tests. The final container is customisable depending on the intended place of installation. The solar wall is divided in units, three of which were prototyped.

The final prototype was produced using a customised pellet extruder mounted on a Comau NJ-60. For the control of the extruder an Arduino running Marlin Firmware was used. Hereby the G-code was embedded in the PDL2 code within Grasshopper. This ensured the needed coordination between movement of the robot and extrusion during 3D printing. For the final prototype a 3mm nozzle has been used. The printing orientation was determined by the inner geometry of the channels containing the thermal materials. Each unit was printed in averagely 20 hours. The total weight of the 3 empty units is less than 50kg.



ADDITIVE MANUFACTURING IN CONSTRUCTION BY EXTRUSION OF LIGHTWEIGHT CONCRETE

Brno University of Technology, Institute of Machine and Industrial Design
Martin Krčma, doc. David Paloušek, PhD.
3dlaboratory.cz



The submitted object is a one of a series of connecting pieces, enabling construction of a wooden beam structure, such as a patio or a pavilion. The beams are 10 cm in diameter. The intent of the design is to showcase material properties and possibilities of using it in the construction industry.

The object is manufactured from polymer concrete, made up of recycled, post-consumer plastic and aggregate (sand). The material has a working name - POLYBET. The main benefit of the material is its decent mechanical strength in tension compared to traditional concrete combined with a low price point due to utilization of waste that would typically be burnt or landfilled.

The printer consists of a Kuka robot arm and screw extruder developed by our department in partnership with ViaAlta company. The prints are performed utilizing 5-axis nonplanar strategies planned in Grasshopper, which allow us to print large overhangs and achieve improved surface quality.



STRUCTURAL MEMBERS MANUFACTURED BY FREEFORM DEPOSITION OF POLYMER CONCRETE

TU Munich, Centre for Building Materials /Chair of Timber Structures and Building Construction
Carla Matthäus, Thomas Kränkel, Daniel Talke, Klaudius Henke
www.bgu.tum.de/cbm, www.bgu.tum.de/hb



Advances in additive manufacturing have opened up new design and production possibilities for a multitude of industrial fields. Also in construction, additive manufacturing methods enable the creation of novel and multifunctional building elements. Here, especially concrete as a building material with its well understood properties lends itself to additive manufacturing.

The different ways in which concrete can be used to additively manufacture building elements is the topic of multiple joint research projects conducted by the Chair of Timber Structures and Building Construction and the Centre for Building Materials of the Technical University of Munich. In this research, depositing processes such as extrusion of light weight concrete (LC3D) as well as particle-bed-based methods, namely selective cement activation (SCA) and selective cement paste intrusion (SPI), are explored.

With additive manufacturing by extrusion of lightweight concrete (LC3D) it is possible to produce formwork-free, thermally and structurally optimized building elements that can be used in the building en-

velope with-out additional thermal insulation. The fine strands chosen for the project enable a high resolution and allow the creation of filigree cavity structures, which are the basis for the functionalization of the building elements. In the project, tailor-made and closely matched solutions were developed for all components of the manufacturing system. Various test objects and demonstrators were manufactured and thus the feasibility of the process was proven.

TAKENAKA CONNECTOR

MX3D
Gijs van der Velden
gijs@mx3d.com



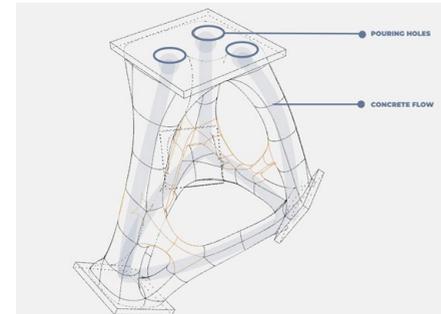
Dutch 3D metal printing company MX3D and Japanese construction company Takenaka designed and printed an optimized metal (i.e. duplex) connector. This project shows the progress in the production of highly customized and engineered structural connectors using robotic 3D metal printing, i.e. Wire Arc Additive Manufacturing (WAAM).

The duplex Connector is designed by MX3D and Takenaka engineers with the help of a topology optimization program that uses the mechanical properties of

the printed material and the design constraints. The Connector has a hollow structure which is filled with concrete. The inner concrete core delays or prevents local buckling of steel, and the outer steel bears bending and tensile forces.

The Structural Steel Connector's net weight is 40Kg, reaching up to 45Kg after its hollow core was filled with approximately 2.5 litres of mortar.

Following the success of this initial concept, the partners involved now intend to implement the next bigger



version(s) in an actual building project. To make this happen a whole new range of MX3D prints is currently being tested in the Takenaka facility.

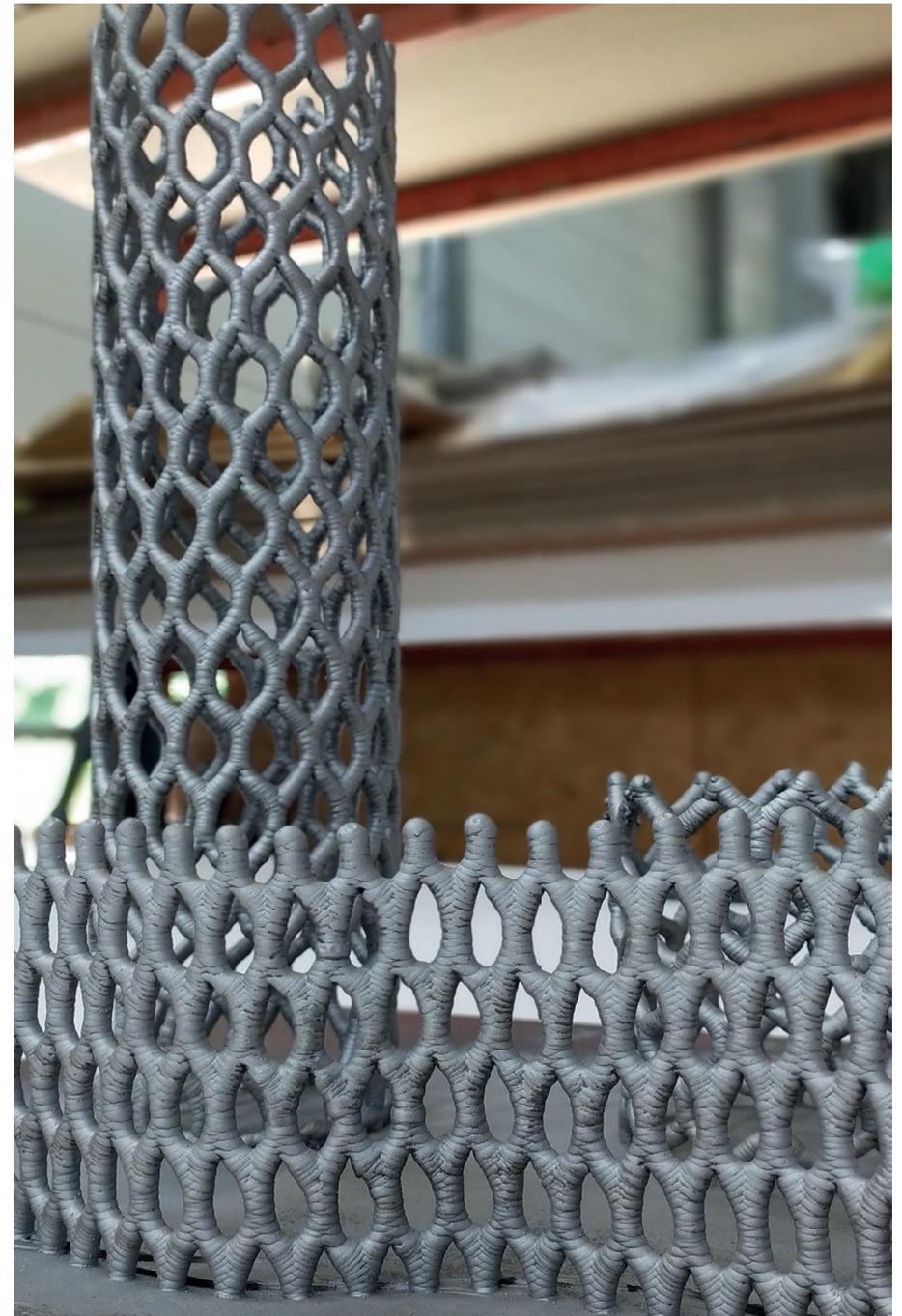
The company is known for its Bridge Project, to be placed in Amsterdam city center in November 2020. The company supplies 3D printing software (+sensors) to others who are interested in 3D printing large structural objects in metal. MX3D employs 18 people and 9 large scale 3D printing cells.

3D PRINTED FUNCTIONALLY GRADED LATTICE STRUCTURES

TU Darmstadt, ISMD
Chris Borg Costanzi, Ihab Said
www.ismd.tu-darmstadt.de



This project explored the use of force-adaptive steel 3d printed lattice structures. By varying the cross section and density of such structures, it is conceivable that more material-efficient free-form structures can be realized. This project forms part of a Master Student research at Technical University Darmstadt



ADDITIVE MANUFACTURING IN CONSTRUCTION BY SELECTIVE CEMENT ACTIVATION

TU Munich, Centre for Building Materials /Chair of Timber Structures and Building Construction
Daniel Talke, Klaudius Henke, Daniel Weger, Thomas Kränkel
www.bgu.tum.de/cbm, www.bgu.tum.de/hb

Advances in additive manufacturing have opened up new design and production possibilities for a multitude of industrial fields. Also in construction, additive manufacturing methods enable the creation of novel and multifunctional building elements. Here, especially concrete as a building material with its well understood properties lends itself to additive manufacturing.

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selective cement activation (SCA) and selective cement paste intrusion (SPI), are explored.

Selective cement activation (SCA) is a type of selective binding method in which the element is created by solidifying certain areas of a dry particle layer. By adding and solidifying layer after layer, complex 3D elements can be created with the surrounding dry particles acting as support. In this case the dry particle mixture consists of a cement binder and aggregate (e.g. sand or lightweight aggregates). A specialized print head is used to apply or „print“ water onto the particle layer according to a digital model. Using this material process combination, very complex concrete geometries in a resolution of up to 1 mm can be produced with material strengths of up to 26 MPa.



ADDITIVE MANUFACTURING IN CONSTRUCTION BY SELECTIVE CEMENT PASTE INTRUSION

TU Munich, Centre for Building Materials /Chair of Timber Structures and Building Construction
Daniel Weger, Alexander Straßer, Thomas Kränkel, Daniel Talke, Klaudius Henke
www.bgu.tum.de/cbm



Advances in additive manufacturing have opened up new design and production possibilities for a multitude of industrial fields. Also in construction, additive manufacturing methods enable the creation of novel and multifunctional building elements. Here, especially concrete as a building material with its well understood properties lends itself to additive manufacturing.

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cal University of Munich. In this research, depositing processes such as extrusion of light weight concrete (LC3D) as well as particle-bed-based methods, namely selective cement activation (SCA) and selective cement paste intrusion (SPI), are explored.

Selective cement paste intrusion (SPI) is a selective binding method which uses cement paste to locally bind thin layers (≤ 5 mm) of aggregates. The unbound particles of the particle-bed act as support which enables the production of complex and overhanging structures. Furthermore, SPI produced objects can achieve a compressive strength of 78 MPa as well as a high durability with isotropic material behavior.



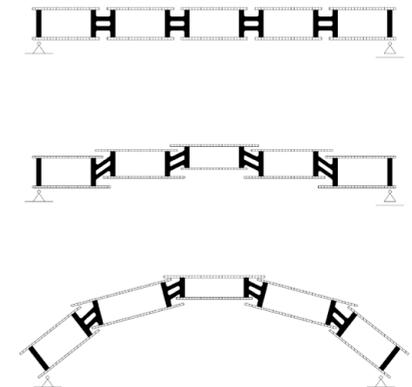
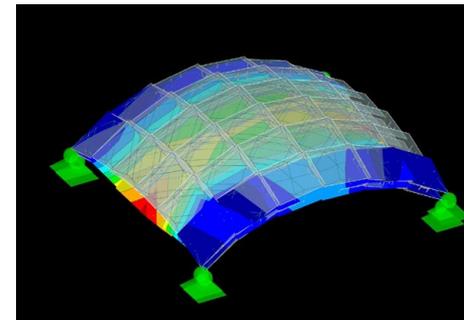
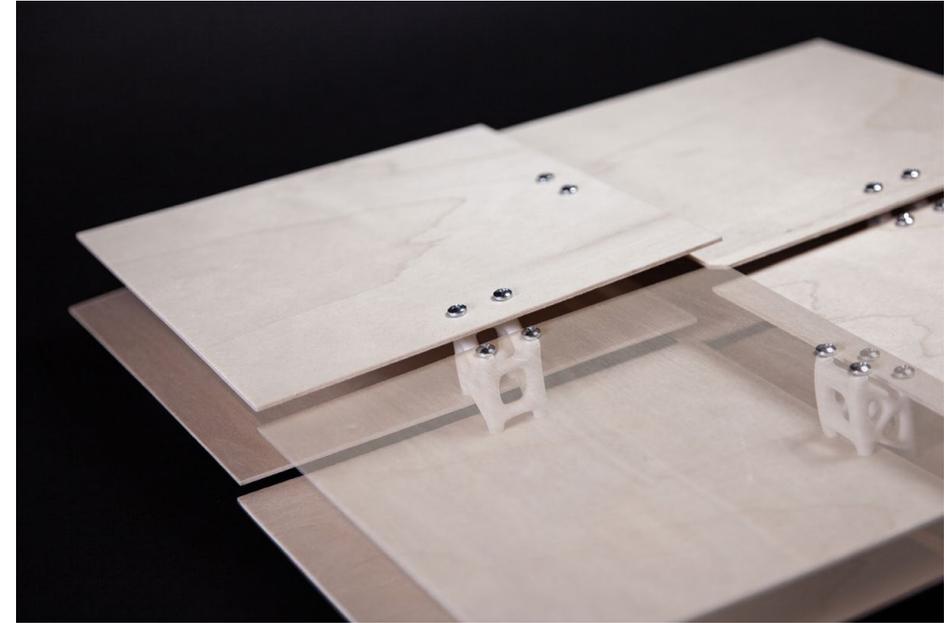
SPACE SHINGLES

Leibniz Universität Hannover, Institut für Gestaltung und Darstellung
Mirco Becker
www.igd.uni-hannover.de/de/dma



The paper describes how established manufacturing methods and certified materials in metal casting are used in conjunction with 3D-printed moulds for creating geometrically complex structural aluminium connectors. To show the potential of this process we propose a novel connector that differs from bespoke tube connectors and traditional spider fittings. We showcase a connector for joining sheet material to form larger double-layered structural assemblies such as decks and shells without the need of any substructure. This includes topology optimization of the connectors towards structure, material use, and casting limitations. It describes the production of individually shaped connectors, which are produced indirectly using a large format binder-jet 3D-sand-printer for casting metal cores. It results in bespoke cast metal connectors with approved material properties.

A possible novel design application of such a plate connector is demonstrated in a shingled double-layered structure. Such varying overlap between panels with relatively large tolerances also opens the possibility for constructing non-standard forms out of standard panels. It also allows to design with reused plates or production-waste material by employing combinatorial methods.



INFO

CONTRIBUTORS

Advanced Ceramics R&D Lab

Prof. Paulo J. S. Cruz
pcruz@arquitectura.uminho.pt
www.aclab-idegui.org

Aectual

Jelle Feringa
jelle@aectual.com
www.aectual.com

CONCR3DE

Eric Geboers
eric@concr3de.com
www.concr3de.com

ETH Zurich, Gramazio Kohler Research

Inés Ariza
ariza@arch.ethz.ch
www.gramaziokohler.arch.ethz.ch

incremental3d GmbH

Georg Grasser
georg.grasser@incremental3d.eu
www.incremental3d.eu

Lithium Architects GmbH

Dr. Holger Strauß
h.strauss@li3architects.com
www.li3architects.com

MX3D

Gijs van der Velden
gijs@mx3d.com
www.mx3d.com

PERI GmbH

Dr. Fabian Meyer-Brötz
fabian.meyer-broetz@peri.de
www.peri.de

Production Technology Group

Dr. Jörg Hildebrand
joerg.hildebrand@tu-ilmenau.de
www.tu-ilmenau.de/fertigungstechnik/

Soliquid

Amaury Thomas
amaury.thomas@soliquid.io
www.soliquid.io

Studio Tessin

Oliver Tessin
tessin@studiotessin.com
www.studiotessin.com

TU Braunschweig, ITE

Prof. Harald Kloft
ite@tu-bs.de
www.tu-braunschweig.de/ite/

TU Braunschweig, ITE

Jeldrik Mainka
jeldrik.mainka@tu-braunschweig.de
www.tu-braunschweig.de/ite/

TU Darmstadt, DDU

Samim Mehdizadeh
mehdizadeh@dg.tu-darmstadt.de
www.ddu-research.com

TU Darmstadt, DDU

Bastian Wibranek
wibranek@dg.tu-darmstadt.de
www.ddu-research.com

TU Darmstadt, ISMD & GASS, imagine computation GmbH, Rossmanith GmbH & Co. KG

Chris Borg Costanzi
borg@ismd.tu-darmstadt.de
www.ismd.tu-darmstadt.de

TU Darmstadt, ISMD

Alamir Mohsen
a.mohsen@li3architects.com
www.building-am.de

TU Darmstadt, IFSW

Prof. Jörg Lange
info@stahlbau.tu-darmstadt.de
www.stahlbau.tu-darmstadt.de

TU Darmstadt, IFSW

Thilo Feucht
feucht@stahlbau.tu-darmstadt.de
www.stahlbau.tu-darmstadt.de

TU Dresden, Institute of Building Construction

Prof. Christian Louter
christian.louter@tu-dresden.de
www.bauko.bau.tu-dresden.de

TU Eindhoven, Concrete Structures

Prof. Theo Salet
t.o.v.d.werff@tue.nl
www.tue.nl

Unipor

Dr. Thomas Fehlhaber
thomas.fehlhaber@unipor.de
www.unipor.de

3DPRIYOL

Seungkyu Yoo
hsysk@3dpriyol.com
www.3dpriyol.com

3F Studio & TU München, PEG

Moritz Mingengast
moritz.mungenast@tum.de
www.3fstudio.de

BE-AM 2020 PROJECT PARTNERS

Collaborators



ISM+D

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Editors

Prof. Dr.-Ing. Ulrich Knaack
Prof. Dr.-Ing. Oliver Tessmann
Dipl.-Ing. Bastian Wibranek, MA

Design und Layout

Dipl.-Ing. Bastian Wibranek, MA
Lara Maria Münscher, cand. arch.

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TU Darmstadt - Fachbereich Bau- und
Umweltingenieurwissenschaften
Prof. Ulrich Knaack
ISM+D Institute of Structural Mechanics and Design
Franziska-Braun-Str. 3
64287 Darmstadt

TU Darmstadt- Fachbereich Architektur
Prof. Oliver Tessmann
DDU - Digital Design Unit - Digitales Gestalten
El-Lissitzky-Str.1
64287 Darmstadt

BE-AM Coordination

Prof. Dr.-Ing. Ulrich Knaack
Prof. Dr.-Ing. Oliver Tessmann
Dipl.-Ing. Bastian Wibranek, MA
Ir. Chris Borg Costanzi, M.Sc.
Philipp Rosendahl, M.Sc

