

BE-AM

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Additive Manufacturing

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SYMPOSIUM
EXHIBITION

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INTRODUCTION

FOREWORD

ULRICH KNAACK & OLIVER TESSMANN

Digitalisation changes the way we design and materialize products and the built environment. Additive manufacturing is only beginning to impact the construction industry. Pioneers in research and practice are printing concrete, clay, plastics and metals in different scales and for various applications. At the same time, designers are exploring the creative and technological potential of additive manufacturing and challenge the way we build today.

BE-AM | Built Environment – Additive Manufacturing is both a symposium and 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 is the first year we teamed up with the Formnext Fair and relocated the event to Frankfurt. We are delighted about this novel collaboration, as it will provide a strong platform for dissemination and knowledge exchange.

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

Q&A



Q&A HARLAD KLOFT OLIVER TESSMANN

Oliver Tessmann (OT) : You conduct research into additive manufacturing with concrete. The topic is currently subject of many other research institutes, as well. What is special about your approach?

Harald Kloft (HK) : In recent years, 3D printing of concrete (additive manufacturing) has mainly been promoted in research by building material technology institutes. Since 3D printing does not work with formwork, the printing material is of course of great importance. The decisive factor is that the material must be dimensionally stable after depositing. At the same time, it is necessary that the successively deposited strands form a good layer bond and that the component has a high green strength in order to prevent collapse due to its increasing dead weight. It is obvious that material and manufacturing process are closely intertwined and have to be adapted to the component design. Our team at the Institute of Structural Design at TU Braunschweig researches innovative 3D-printed concrete components and works closely together with building material technologists and process engineers. The focus is on the production of resource-efficient concrete elements with structural logic and material-saving design. The novel technology of additive manufacturing makes it possible to control the manufacturing process in such a way that material is only applied where it has a function. This gives us

the freedom to identify new approaches to optimally match material, process and structural design: We aim, so to speak, developing a new logic of form for additive manufacturing.

OT : Extrusion is a broadly employed method for additive manufacturing of concrete. At TU Braunschweig, you work with pressurised air, borrowed from the well-established sprayed concrete technology. Can you explain the principle behind your method?

HK: Gladly. Like with extrusion we deposit the concrete along predefined paths. However, we introduce pressurised air into the concrete matrix before it reaches the nozzle, thus accelerating it similar to sprayed concrete. If we omit the pressurised air, it is a common extrusion process. We call this pressure printing process "Shotcrete 3D printing (SC3DP)". The big difference is that by introducing kinetic energy we achieve a significantly improved layer bond. Our Digital Building Fabrication Laboratory (DBFL) at TU Braunschweig allows robot-aided, additive manufacturing of large building components. However, the printed parts cannot yet be applied to building practice. Current norms and regulations related to common, reinforced concreting do not yet provide for this type of manufacturing process. But we do hope that the norms that have been established in the field of sprayed concrete for years,





particularly used in tunnel construction and similar areas of application, will help to put our method into practice faster than pure extrusion processes.

OT: Thus, an established technology is employed in a new context.

HK: That's right. The shotcrete technology is already available and we hope to benefit from the experience we have. However, the shotcrete is still applied manually. We have designed the SC3DP process from the ground up as a robotic process to develop robust automated additive manufacturing processes for the construction industry. This novel digital process will hopefully help to quickly transfer the technology into practical building applications.

OT: How about reinforcement? Can you adopt technologies from sprayed concrete in this area as well?

HK: We have already conducted several large-scale trials. At the moment, we integrate conventional reinforcement steel in order to avoid having to research the bond between concrete and reinforcement material. The challenge hereby is to completely cover the steel with the sprayed concrete, such as we make sure when concreting and compacting conventionally. Just recently, we were able to create steel-reinforced concrete columns as part of a case study experiment by integrating reinforcement cages. We cut through the columns and ran a Micro-CT scan to examine the bond and to ensure that the reinforcement was indeed fully covered. The results are very promising.

OT: In your opinion, what are the greatest challenges in transferring your research into building practice?

HK: I think that additive manufacturing of concrete will become a key technology for the building industry, for two main reasons:

1. It is a digital manufacturing method that can be ideally combined with the new, digital planning methods of Building Informati on Modelling, and
2. Additive manufacturing has the econo

mic potential to displace traditional techniques.

Even twenty years ago, we realised new, free-form architectures. Even though the building components were manufactured using digital technologies from other industrial fields, they were still manually assembled onsite. It was not economically viable to simply transfer technologies suited for serial production to individualised building projects. In contrast, additive manufacturing is ideally suited for the building industry. For the first time we are dealing with a technology that can map the digital fabrication economically, as well, and that fits well with our building processes. Hitherto, there was no technology that could truly compete with manual building. Therefore, in my opinion, it is the first technology that really has the potential of economic viability. This also shows in the great interest that the industry has in our method. We rely on the proven technology of sprayed concrete, and develop it into a new, digital manufacturing technology that the industry can benefit from.

As mentioned before, one of the challenges concerning the transfer into practice will be the building regulations. Of course, the building industry requires processes that comply with building regulations and specifications. Another challenge are the digital interfaces. Our sequential processes planning, tendering, manufacturing do not match digital process chains. Therefore, the goal must be to consider the boundary conditions of manufacturing as early as in the design phase. Which, in turn, means that we also need new, digital design tools.

OT: Does that mean that all of today's planning and building processes could or should be disposed of?

HK: No, I would not go so far. Many established building technologies will continue to exist. Additive manufacturing will not replace all other technologies; rather, it is a new technology that should be integrated where possible and sensible. Many building projects will continue to require formwork. It does not make sense to print straight, massive concrete walls. The



great opportunity lies in integrating the know-how and the possibilities of additive technologies into design and planning, in order to create resource-efficient and sophisticatedly designed buildings that would not have been economically realisable otherwise. For example, we can print mushroom-shaped support columns. A shape that solves the issue of punching shears geometrically, not via elaborate steel components. Currently, mushroom columns require elaborate formwork, which renders them uneconomical and therefore rarely used in today's buildings. Additive manufacturing makes them easy to build. Ribbed ceilings are another example: the thickness of a traditional 30 cm thick, massive ceiling slab can be reduced down to 10 cm; the 10 cm thick slab is concreted traditionally, and the ribs are then printed onto it. Such hybrid processes save material and free up space for installations. The ribs could also be used as structural ornaments, such as Pier Luigi Nervi employs in his designs. It is as easy to print a curved line as a straight one.

OT: What is your vision for future building?

HK: My vision is to think building in a new manner. I would like us to design and build future buildings of high design and technological quality, based on an automated design and building process that, however, yields unique buildings. Additive manufacturing processes promise exactly that. In the past, we realised impressive buildings with an unbelievable expenditure of work and money, while reinventing the wheel every single time. This is not how to efficiently advance an economic sector. My idea is to provide architects, engineers and building firms with a technology that offers a standardised process, yet free forms, as well. If we succeed in offering that for the building industry, we are even ahead of the other industry sectors. Mechanical engineering and the automotive industry are already trying hard to apply additive manufacturing. However, these sectors are serial production orientated. Most buildings, on the other hand, are one of a kind. We consider it important that we have a process available that is suited for serial production but can also efficiently generate individual parts.



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Q&A THEO SALET ULRICH KNAACK

Ulrich Knaack (UK) : Why print concrete?

Theo Salet (TS) : I would like to make the question even more poignant: why print concrete since it is a liquid material that is certainly not the easiest to print?

One reason to print concrete is that concrete still is one of the major materials that we need to fill our worldwide needs for buildings and civil infrastructures. Maybe we can find a different or a better material in the future, but not in the short term.

But for now, if we want to work on sustainability in our world, we have to start printing concrete using additive materials, additive manufacturing, and we need to place material exactly at those places where we need it, thereby cutting down on the overall amount of material used.

UK: So that it to say the central benefit of printing concrete is that you deposit the material where you need a structure, and not where you don't, which you would do when casting concrete as a solid structure?

TS: Yes! If you phrase the question: why do you print concrete, with the emphasis on that final word, you pose the question because concrete – contrary to a lot of other materials - has a negative impact on sustainability. We use a lot of raw materials because we build big things, we cannot do anything about that because structures are inherently big. But concrete has the downside of high carbon dioxide emissions resulting from using cement

as a binder. So, printing concrete versus using other techniques makes sense because we can cut down on the amount of cement we use and the raw materials. To me, the sustainability impact when working with concrete is important.

UK: That makes sense. But what kind of key problems do you face when printing concrete?

TS: Actually, there are two main problems, and maybe a third. I will describe the first two in a little more detail, they are related to each other.

If you print too fast with a wet material - you can call it a liquid, I call it mud – so if you print too fast the result is not stable and will become instable due to buckling, which causes a stability issue.

But if you print too slowly, the two layers on top of each other do not bond well. Just like masonry work, if you have a dry brick and you place it on wet mortar it will absorb the water from the mortar, and the bond is poor. Luckily, there is a small window that yields good results, which means you should print neither too fast nor too slow. Finding that window of opportunity is the first issue you face to produce good printed material.

The second issue is that, more often than not, you need to produce a composite material, reinforced concrete, as it is usually called. If you don't, you end up with a material that has good compressive strength, allowing for Gothic architecture. There is nothing wrong

with Gothic architecture, but it limits you. So, if you want to employ concrete for other applications, you have to reinforce it and create a composite. This is the second challenge.

The third issue I mentioned is a completely different one. It is good that we can print concrete, and that we have additive manufacturing, so that we can place concrete systematically. The first question was: why do we want to place it, but the next question is, where do we place it. We need algorithms to optimize our structures in a way that they can be printed with a particular printer.

UK: Understood, but concrete reinforcements, part of challenge 2, how do you solve that? That seems to be the key problem in all the printed concrete projects.

TS: The first thing we tried out is a bit of a story and you can choose for yourself what you think is the most interesting part. The storyline is that we first started very traditionally. We printed a couple of layers concrete on top of each other. And then it took a robot and a lot of manual labor to insert reinforcement, traditional reinforcement bars, in the printed material, and then to simply keep printing on top of it. If you have a very small rebar compared to the layer of the thickness that you print the method works but do realize that the mortar is shape-stable. So, if your reinforcement bar is very thick relative to the layer thickness there will be voids, air voids around some parts of your reinforcement, which reduces the durability of the steel reinforcement.

Therefore, we tried a second, different approach. We embedded wire reinforcement immediately during printing. We had a great supply of wire; during printing, the wire unwinds and disappears immediately in the concrete filament that we print. Since this method worked well with one wire, we fed two or more wires in with the concrete mix - the wires can be steel. Later we replaced the steel with glass fibers from a roll because they cannot corrode, which improved the process significantly. The third option we tried out was working with loose fibers. We developed a tool that is installed near the print head and adds fibers to the concrete right when it is dispensed. The fibers make the concrete more ductile. To sum it up,

fibers make it more ductile and wires make it stronger. So, we can employ methods to achieve higher ductility and higher strength, and we can combine the two properties as appropriate for a particular project.

And then there is another, completely different answer: pre-stressing – which we did with the bridge. Pre-stressing unreinforced concrete is another way to overcome tensile strength related issues.

UK: You mean that the bridge is composed of prefabricated components, and then pre-stressed as a whole?

TS: Yes. In that case the components themselves do not have to be pre-stressed. It more or less resembles Gothic architecture because the dead weight has pre-stressed the structure by itself. Which makes it strong enough to withstand wind forces. If you apply the same trick, but now with external pre-stressing, you pre-stress unreinforced components and make them pre-stressed in terms of compression to give them a certain degree of tensile capacity.

UK: Understood – so my next question is: will entire buildings be printed in concrete in the future?

TS: My answer is: why should we? Which means I am posing a question in return. I don't see any reason why we should make the technology more important than the end goal. The end goal is to create very good buildings, and to create a very good building we can use all technologies that are available. So, for those parts for which it makes sense to use 3D printers, we use 3D printers. The objective is to make a good house, not a 3D printed house.

UK: My last question is aimed at the person who very much boosted concrete printing: from your point of view, which are the most promising materials for additive manufacturing besides concrete?

TS: That is a difficult question to answer for a professor in concrete structures.



UK: That is why I am curious to hear your answer.

TS: Since you asked me to limit my previous answer a little, I will take a little more freedom to answer this one. At NTU in Singapore I print with geo-polymer concretes. I am very interested in doing more research in this field because it helps to create a stone-like material which could be beneficial for our structures, civil structures as well as buildings because the material is fireproof, amongst other properties. Meaning that concrete might

maintain its space as an important building material in the future, but rather in the form of a geo-polymer, without the cement as a binder. This is what interests me.

And besides, I am really interested in working with bio-based materials because I think that should be the future of our society.

UK: Smart answer for a professor in concrete construction! Thank you very much for your time!





Q&A AMAURY THOMAS CHRIS BORG CONSTANZI

Chris Borg Constanzi (CBC) : What made you choose to work with Additive Manufacturing for construction in the first place?

Amaury Thomas (AT) : Launched in Paris in 2018, Soliquid is a startup that specialises in additive manufacturing and develops a unique large-scale 3D printing process in suspension in a reusable and durable gel matrix. Amaury Thomas and myself are architects, we specialised in computational design and robotic manufacturing. The company Soliquid was founded together with Impulse Group – the objective was to broaden the field of 3D printing by proposing innovative logics and processes for the production of non-standard, tailor-made, complex and unsupported elements for multiple industries.

The initial and main objective of Soliquid's creation was to develop our 3D printing process in order to revolutionise prefabrication in the AEC (Architecture, Engineering and Construction) and Design sector, by proposing a new industrial production method for constructive, complex and custom-made elements, lighter and more efficient, without the use of moulds or supports. With this process, a wide variety of applications can indeed be imagined and are beginning to emerge. They range from the optimisation of structural systems (slabs, columns, beams, building modules...), to the

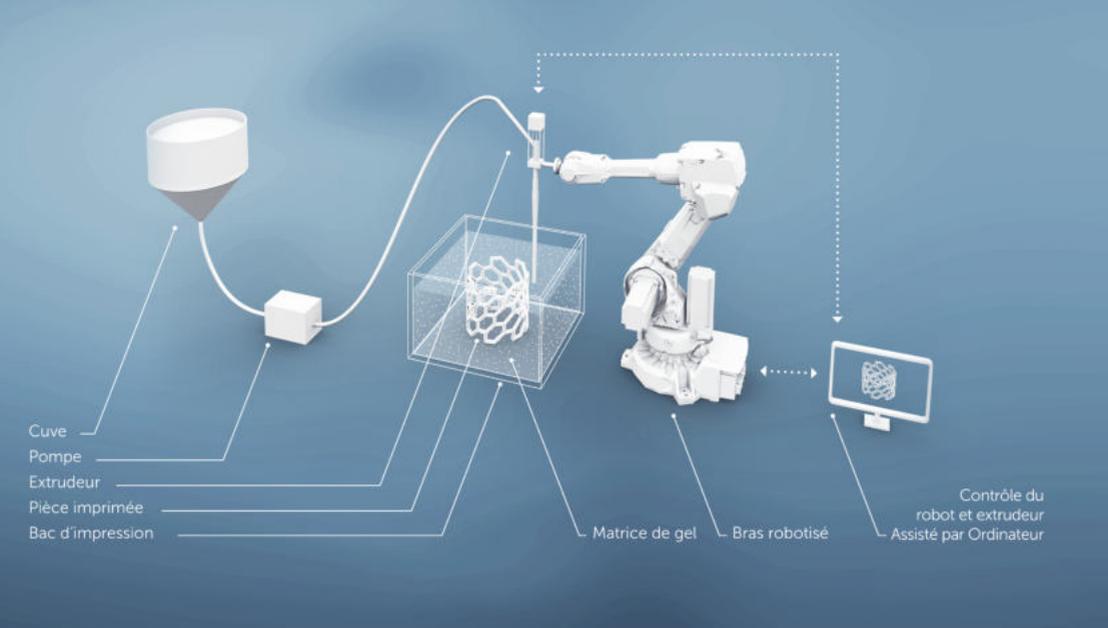
manufacture of non-standard architectural elements (façade panels...), to the production of innovative furniture ranges.

CBC: Soliquid is a unique method for 3D printing in suspension - could you explain shortly how the technology works, and how you see this technique as being beneficial over other traditional printing methods?

AT: Our patent pending large-scale suspension 3D printing technology differs from "layer by layer" 3D printing in that the printing material is deposited in a gel matrix rather than on the previous printing string.

The general device consists of a printing tray that contains a gel matrix and a 6-axis industrial robot, at the end of which is fixed the print head we are developing. This set consisting of the robot and its end-effector is directly controlled on a computer. It's on the computer that the printing phase is prepared and then initiated: the 3D model of the element to be printed is analysed, adapted if necessary, then converted into 3D curves corresponding to the future toolpaths of the robot during printing. This path is then broken down into a succession of planes in the XYZ space and associated with certain parameters that define the specifications of the movement and printing processes. The software we use allows us to convert this data into RAPID language, used to control the robot. All the printing characteristics





such as the toolpath, the robot's movement speeds, but also the start/stop of the print and the variations in its flow rate are therefore programmable.

In parallel, a pump is used to bring the printing material from the storage and mixing tank to the print head. When printing starts, the print head fed by the pump plunges into the printing tank and deposits the printing material following the previously determined toolpath. This is where the specificity of our technology comes into play: rather than casting, the printing material is kept in suspension in the matrix, thanks to a clever balance between viscosity and density in the materials used.

At the end of the printing phase, the element is kept suspended in the matrix, thus acting as an adaptive formwork/mould/support, until its solidification, or hardening, is sufficient to allow its removal from the tray. Once the part has been extracted, a new print can be done in the same tray; the stability and durability of the printing matrix allows the process to be repeated many times over long periods of time with the same initial volume.

Many players in the construction and building sectors are now trying to adopt additive manufacturing technologies as a production strategy. To date, however, the latter play a very limited role in industrial processes, for four main reasons: production time, scalability of the device, material and formal limitations.

With a unique concept, the process we are developing responds to the challenges raised by existing additive manufacturing techniques with three major differentiations: printing speed, morphological (design) freedom and material saving: using a gel matrix to keep the printed material in suspension, our printing strategy does not require any support materials. The material can therefore be continuously injected without requiring its progressive solidification during printing, making the printing process extremely fast. We are not restricted to the 'layer by layer' feature of most 3D printing techniques, therefore we can allow extremely free toolpaths in terms of direction and orientation of the extruder in the 3D space. Thanks to the topology optimisation tools we use, the printing of an element can be programmed to be optimised in three dimensions and at different levels: material quantity

reduction, carbon emission reduction and structural performance. Our suspension technique also makes it possible to consider new printing possibilities, which are difficult to implement with conventional 3D printing processes. For example, parts can be printed according to intricate principles (e. g.: one inside the other, chain links connected to each other, etc.).

CBC: How do you think advances in digital design tools will shape the design process in which Architects (and Engineers) conceive the built environment and what do you imagine for the future?

AT: The role and capabilities of the architect, designer and engineer are continuously evolving. Many of the new skillsets that are being acquired (such as coding and advanced 3D modelling) are enabling those involved in the design and construction of the built environment to conceive more complex forms and spaces. The lines between architect, engineer and fabricator are also being blurred thanks to advances in such technologies.

However, I don't believe that 3D printing will completely take over other established fabrication techniques currently used in construction – we will still continue to build in many techniques used today. 3D printing will serve as another tool for architects and designers to more-freely express themselves in the context of an ever-increasing digital word, and allow engineers and fabricators to more creatively solve problems.

In the future I believe things will get smaller and modular; printers do not need to be the size (or larger) than the object they are printing as is the case that commonly happens now. Instead, I believe we would see a building site crawling with swarms of autonomous mini-fabricators working collectively to construct our buildings.





Q&A THOMAS FEHLHABER ULRICH KNAACK

Ulrich Knaack (UK): Hello, I am speaking to Thomas Fehlhaber, head of Unipor, one of the largest brick manufacturer associations in Germany. Welcome Thomas! Thomas, since when is Unipor active?

Thomas Fehlhaber (TF): About 40 years – we started in the mid-seventies with more than 30 family run brick manufacturers with the purpose to develop bricks. The same time we came directly in a market consolidation process. A breather - a lot of building activities after The Berlin Wall Fall - and investigations in a new type "grinded brick" enabled faster laying of bricks on site and energy saving houses without an additional insulation. After another two decades we provide bricks even for passiv-houses. After the consolidation processes in the past our market share in the German brick market is still between 20 and 25 percent with 8 companies - the main drivers in the brick market in Germany.

UK: Thanks for the introduction. As this interview deals about 3D-printing for bricks I would like to have your opinion about this field. And then when I think about it my obvious first question is: Why would we print bricks? What is the reason to get to serve this weird idea of having this kind of "liquid" material being printed and hoping to get it shipped to something solid.

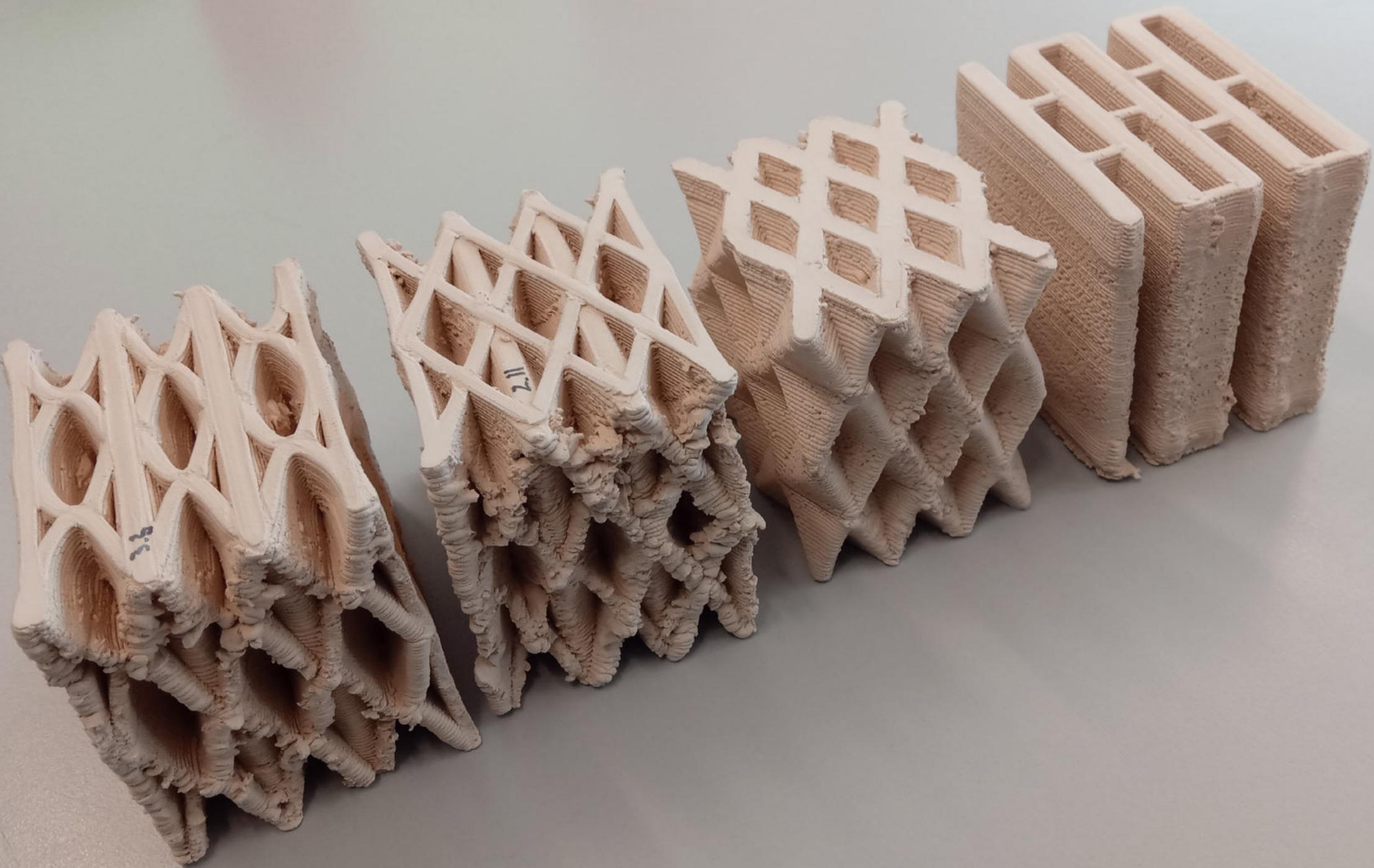
TF: Yes clearly, clay is not easy to handle. Even

we use production processes which are basically more or less the same since a couple of hundred years. 3D-printing appears to be a challenge. We have a lot of experience in extruding clay but the products are still two-dimensional. This needs to change!

There are a lot by application driven - say fired clay products, which we cannot design in an appropriate way, as they need to be produced in a 2-dimensional extrusion process and need to be adapted on site. Thus we decided to look into a manufacturing process which offers us the way into a sort of three dimensional designs.

However there is a second motivation coming from the extrusion process itself. There is a difference in the recipes for clays used for mass extrusion and those pressed through a comparatively tiny nozzle in a controlled process to print in 3 dimensions. For mass extrusion of bricks we handle clay more or less just from around the corner qua location, whereas in the

3D-printing process high performance clays adapted to the high pressure in the print-head are used, which needs to be studied. Those exercises improve our knowledge for the classical brick process, too.



UK: Okay, understood. And after this extrusion process in 3D-printing has happened, the bricks have to be fired, right.

TF: In order to achieve a durable and robust product for the market, Yes.

UK: ok, nice direction. Next step: so could you imagine entire houses to be build with printed bricks?

TF: OK let's say that's what the standard bricks have to be made for: for a normal house we use hundreds or thousands of standard bricks. But for this 3D-printing process I assume it's possible to adjust just a few to the application in the brick facade.

UK: Which kind of bricks are you targeting? Which bricks are the ones you're interested in, and how is this linked to the use of mortar?

TF: Today we have more prefab products on the building site with a supply of a wide assortment of brick products we may choose from when designing a single house. A century ago we had a "one size brick to fit all". Thus building parts were produced on site. Less educated people on site today assemble even more sophisticated building products.

Coming back to your question. The products we are looking for, solve the issues coming up with heat bridges i.e. the embrasure of window openings or a solid ground for mountings with heat insulation properties.

UK: Understood, so the idea is not to print the parts of an entire house, but to print the ones which have to be individual, next to the ones which are standard.

TF: We do not believe in a system where we could print a complete house whether prefab or on site. In brick-construction it will be a combination of standard bricks and 3D-printed bricks. Anyway bricks need to be fired in a furnace.

However, we all are pushed in the direction of a circular economy, where down-cycling of products and materials is minimized. Thus we need to develop a disassembling strategy for brick houses focused to

reuse building parts. Interlocking bricks need to be designed in a 3-dimensional manner. Therefore it is necessary to develop the strength of 3D-printing as technology.

UK: So you say, you have to develop a pre-industrialized process? And what are the key technology problems you're currently facing.

TF: Correct – we have to control the pathway of the printer-head/nozzle and also at the same time the extrusion device has to deploy the right amount of clay. Simple task. But clay doesn't behave like a liquid. Changes in pressure may change the clay properties. The nozzle has an exit more or less 3 to 5 millimeters wide. The pressure necessary to keep the clay moving is about 1,5 MPa. The clay flakes are at least partially charged electrostatically. When the flakes get oriented under pressure the flow of clay may decrease rather than increase. In some cases the material flow breaks down as the clay gets rock-solid - interesting problem! Finally the quality in terms of grain size and chemistry of clay completely differs from place to place. So once you have dealt with a certain clay and know how it works, you need to develop this again or to adjust it again for a different source of clay.

UK: I can understand there is a need of identifying the adjustments you need to do and to run this. Then the obvious next step will be to bring this to a more industrialized level.

TF: Yes, that's right. Industrialization will be the key for the success of the idea. To me the development of a vision of what you think is possible, no matter technology no matter budget to investigator, is needed. This is the start - what will be in the end, we see in in future.

UK: Tell us more about such a vision!

TF: There are two ways for a future vision: One funded in the new opportunities of geometry: Use of new geometries which are offered by the 3D-printing



and their application. This in some cases can be driven by starting from a heat insulation idea. Others are driven by the bearing loads and forces the geometry can cope with in a better way.

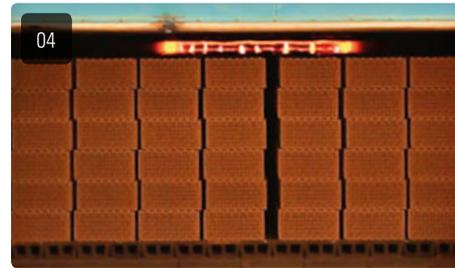
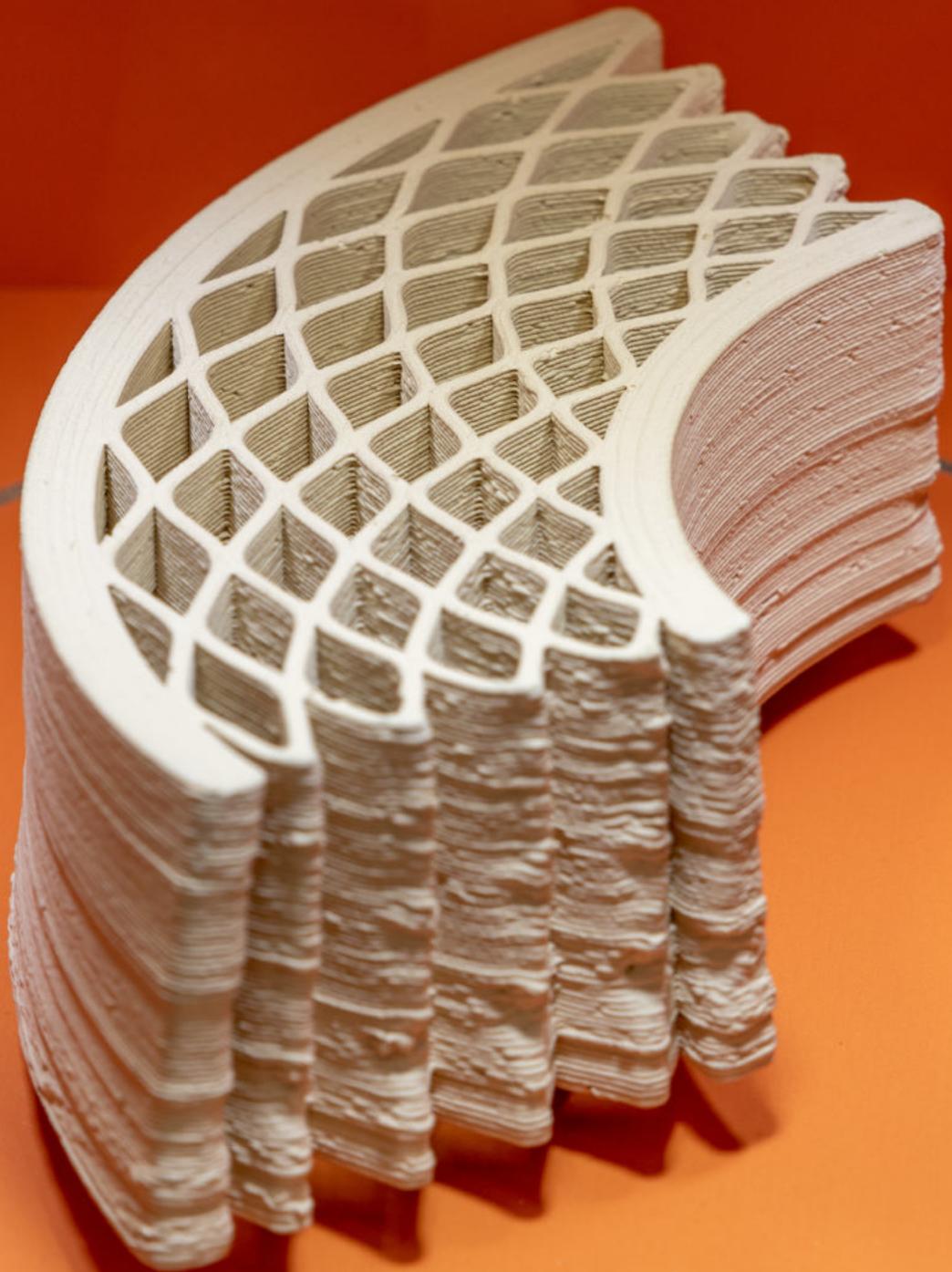
The second one is more alert: We use clay material out of the pit more or less like it is and there is no instrument for conditioning of the clay itself. But we think of opportunities from the research results we can use also in the classical 2-dimensional extrusion process: this would be high end material. However it is something which needs much more investigation.

UK: Certain applications in the extrusion process, that's an interesting one for next and new products you going to create by 3D-printing. That would be a bounce

back effect to the existing technologies by improving the material quantities to make them better to be extruded, or?

TF: Well, as said, we do not believe that 3D-Printing will conflict the already developed and used extrusion processes. There will be a parallel development, in which 3D-printed bricks will enable the common technology to serv additional functions, additional geometries and new needs in a circular economy even in the housing market.

UK: Clear statement – thanks for the interview!

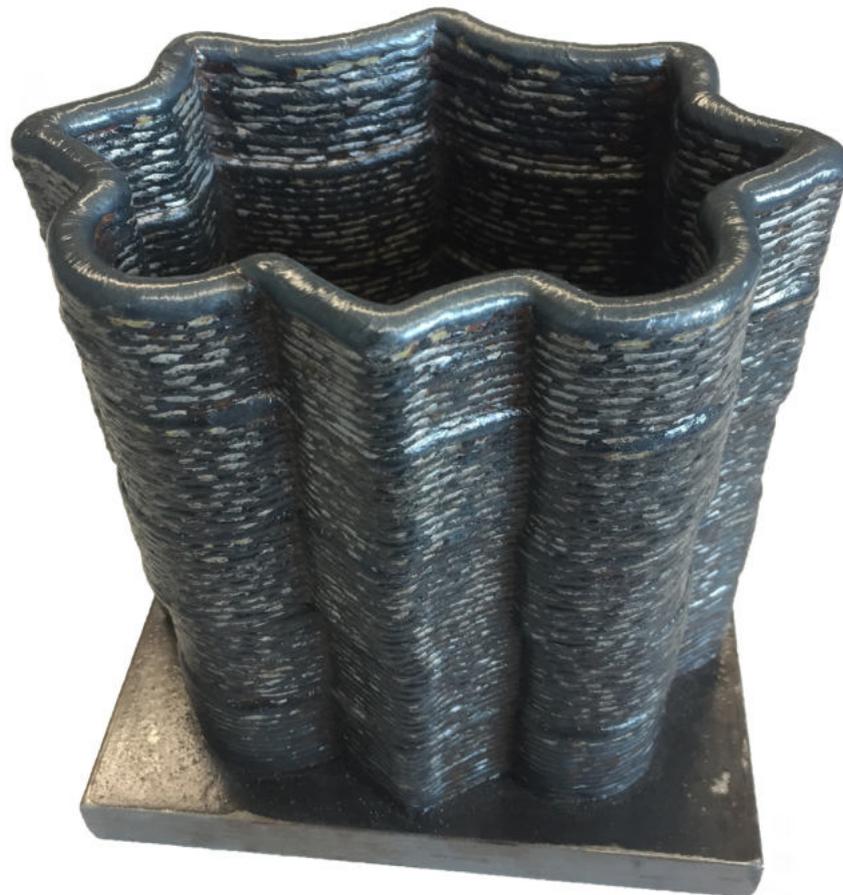




ESSAYS

3-D-PRINTING WITH STEEL: ADDITIVE MANUFACTURING OF CONNECTION ELEMENTS AND BEAM REINFORCEMENTS

PROF. JÖRG LANGE, THILO FEUCHT, MAREN ERVEN
TU Darmstadt, Institute for Steel Construction and Materials Mechanics



Abstract

Automated production is already finding its way into steel construction fabrication. A robot holds attachments (stiffeners, head plates, etc.) to a steel beam and another robot welds them. However, welding robots can also be used for additive manufacturing (Wire + Arc Additive Manufacturing, WAAM). The wire electrode serves as printing material. The Institute for Steel Construction and Materials Mechanics is investigating how typical connecting elements of steel construction can be printed directly on steel beams using Additive Manufacturing with arc welding and robots. The main focus is on determining suitable welding and process parameters. In addition, topology optimization is used to search for structures that are made possible by the free design possibilities of 3-D-Printing and thus to develop novel design and production strategies.

Introduction / Additive Manufacturing

The technologies of 3-D-Printing and Additive Manufacturing (AM) are progressing rapidly. The printing materials are manifold and also the printing of steel is now easily possible. In Additive Manufacturing, a component is created by adding material, as opposed to milling, which removes material from a body. Selective Laser Melting (SLM) and Selective Laser Sintering

(SLS) exist for the Additive Manufacturing of steel [1]. A further method is Laser Metal Deposition (LMD), in which a metal powder is applied to a local molten pool generated by the laser [2]. All these methods are of high accuracy, but also associated with high equipment costs.

For steel construction, Wire + Arc Additive Manufacturing (WAAM), which is similar to Gas Shielded Metal Arc Welding (GMAW), is suitable [3]. The wire electrode serves as printing material. With this method, it is possible to produce large components in layers (see Figure 1) and achieve deposition rates of more than 5 kg/h [4].

Additive Manufacturing in general and the welding process WAAM in particular make it possible to use the material in a targeted manner. Structures can be freely modelled and get almost any shape. Unlike conventional steel construction, economical production hardly limits the form of construction. The customary trade-offs between a cost-effective production and material saving can be omitted. Material only needs to be placed where it is necessary. It therefore makes sense to determine these structures by means of a topology optimization. This leads not only to reduced material consumption but also reduced production time.

Figure 1. Additive manufactured structure (height 13.5 cm)



Figure 2. a) Double angle connection



Figure 3. b) Beam hook (animated)

Topology Optimization

As part of the structural optimization, the topology optimization is suitable for „cutting out“ unstressed areas of solid components and thus increasing the effectiveness (in kN/kg). The topology optimization pursues the lightweight construction approach of material-saving. The objective is to guide a load from load introduction point to support. For example plates are disintegrated into truss structures and thus the structure adapted to the flow of force [6]. In principle a severe reduction of material is desired while the rigidity and the load-bearing capacity stay as large as possible. This approach leads to an optimization problem and guarantees economic added value, since the resource steel is used only at the statically necessary places.

Possible Applications

This research project concentrates on connection elements whose mass is low compared to the entire structure and which can be „printed“ using automated welding robots. Some examples are shown, which are examined at the Institute for Steel Construction and Materials Mechanics of TU Darmstadt.

Beam Hook

Connections of beams to columns are often designed as flag plate or with double angles (see Figure 2a). With Additive Manufacturing it is possible to place the beam on a topology-optimized hook by using bolts (see Figure 2b). The hook can be welded directly onto the column during fabrication. Erection is simplified by eliminating the need for a bolted connection.

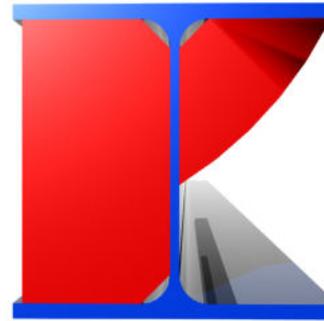


Figure 4. Stiffener in H-Beam

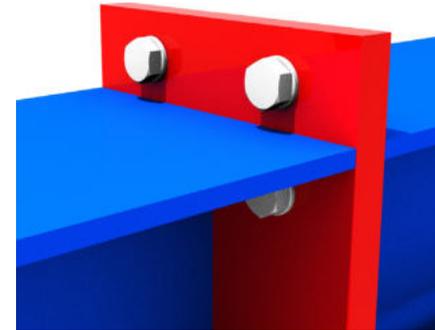


Figure 5. Head Plate / T-Stub (conventional)



Figure 6. Head Plate / T-Stub (topology-optimized)

Stiffeners

Stiffeners are often used for better load transfer into an I-profile and to prevent the flange from bending or buckling. Figure 4 compares a conventional stiffener (left) with the topology-optimized stiffener (right) to be produced additively. In traditional production, unloaded areas would not be removed, as this would require additional effort and the waste would not be usable.

Head Plate / T-Stub

In the case of rigid connections with head plates where moment and tensile force are transmitted with a height offset, since the screw connection is not at flange height (see Figure 5).

The tensile force is transmitted from the flange to the bolt by bending the head plate. The geometry of the head plate can be changed by optimization in such a way

that the effectiveness increases and less material has to be used (see Figure 6).

Nodes in Space Frames

Nodes can be defined as connecting points of steel members such as beams, girders and columns. Fabrication and erection should be simple and cost-efficient. Therefore designers tend to create details that might use very much material in order to reduce complexity in fabrication and erection. Sometimes this cannot be avoided due to the complex geometry of the node. With the help of additive manufacturing nodes might be fitted individually to the load case(es) and the geometry of the members that have to be connected. Especially WAAM seems to be a helpful approach for steel construction due to its big deposition rate and inexpensive equipment. Structures can be designed

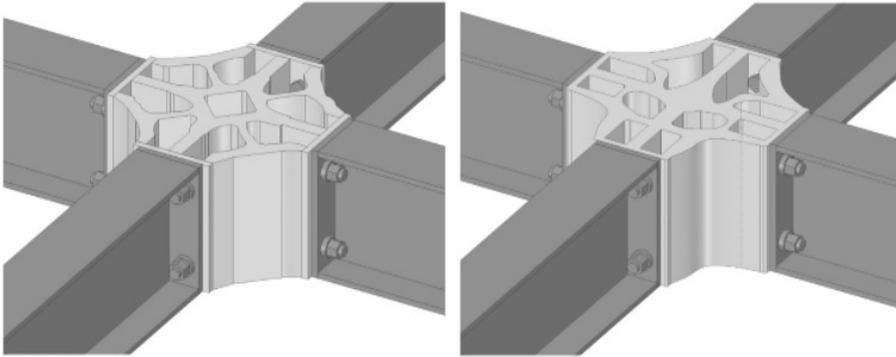


Figure 7: Nodes in a space frame

according to the flow of forces using methods of topology optimisation. This avoids material in places where it is not needed. Figure 7 gives two examples for the connection of four beams in a common plane but with different loading – symmetrical in the right side top, not symmetrical in the right side bottom picture.

With regard to the WAAM it has to be kept in mind, that small overhanging seams might be printed but that it is impossible to print in the air. This has to be regarded in all optimisation procedures. Therefore extruded, wall-like structures are suited very well for this process. Areas where seams meet or cross over each other might be challenging. Double-deposition will lead to distortion, other approaches can lead to voids or incomplete fusion.

Implementation within the context of automated manufacturing

In fully automated manufacturing systems, steel beams are automatically provided with connection elements (e.g. head plates, stiffeners). The elements are scanned, delivered by handling robots and fixed to the steel girder with the help of welding robots (see fig. 8) [7]. In addition, the connection elements can be applied directly to the steel beam with the aid of Additive

Manufacturing. This simplifies the production chain of the connection elements: steel plates for stiffeners, head plates, etc. are not needed any more. This reduces material handling, transport and storage. There is no more waste, which would otherwise have to be stored or disposed of. Instead of a handling robot and a welding robot, two welding robots can additively produce at the same time.

Influences on geometry and material properties

For conventional and commercially available 3-D-printers, parameter sets exist that allow almost any geometry to be printed without the need for any investigations. Slicer programs divide a 3-D body into paths, which the print head travels at a corresponding speed and applies the material in such a way that the planned structure is created. For the WAAM, various parameter investigations already exist, which are very widely scattered with regard to material (steel, aluminium, titanium, alloys) and production equipment (power source, robotics), but they cannot be applied in any case. Especially the required parameters for this particular research project are very complicated due

to the complex multilayer geometries. It is therefore inevitable to gain knowledge of further parameters. This becomes clear when one looks at the many influences that affect the geometry and the material properties.

Input parameters

- Wire electrode
- Wire diameter
- Shielding gas
- Gas flow rate
- Geometry of the gas nozzle
- Welding System

Process parameters

- Current
- Voltage
- Wire feed speed
- Welding process regulation (normal, pulse, CMT)
- Travel speed

Thermal boundary conditions

- Interpass temperature
- Temperature history / temperature cycles
- Cooling

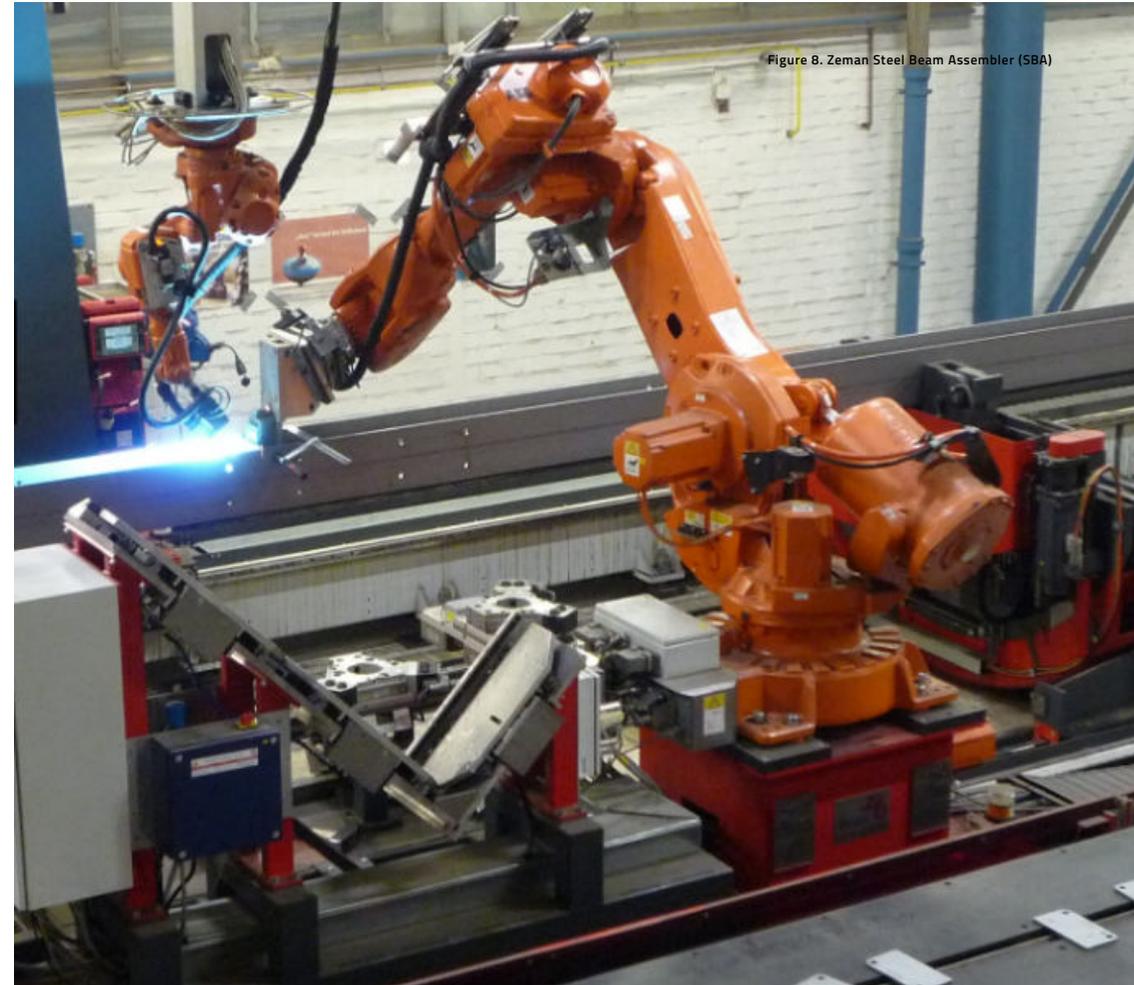


Figure 8: Zeman Steel Beam Assembler (SBA)



Figure 9. Beam Hook (additive manufactured with milled hole)



Figure 11. Full stiffeners in I-beam (conventionally manufactured)



Figure 10. Full stiffener in I-beam (additively manufactured)



Figure 12. Half node of space frame (© gefertec, Berlin)

Geometric boundary conditions

- Orientation of the nozzle (neutral, dragging, piercing)
- Welding position (trough position, rising, falling)
- Contact tip to work distance
- Weld seam beginning, weld seam centre, weld seam end

Previous investigations

Several preliminary tests have already been carried out at the TU Darmstadt.

First results

First tests have shown that structures can be produced linearly on steel beams. A topologically optimized beam hook was produced on an I-beam without any noticeable welding distortions (see Figure 9).

Furthermore full stiffeners were welded into an I-beam (see Figure 10). Despite recognisable welding distortions, destructive compression tests showed that the bearing loads of the additive manufactured stiffeners were at the same level as those of conventionally manufactured stiffeners (see Figure 11).

Half of a node for space frames was manufactured additively. It is shown in figure 12. In this picture the good quality of crossing and touching welds is visible

Conclusions

Additive Manufacturing makes new structures possible, because the constraints of conventional manufacturing no longer exist. More complex and topology-optimized constructions can thus be realized. In this paper, some new connection elements are presented.

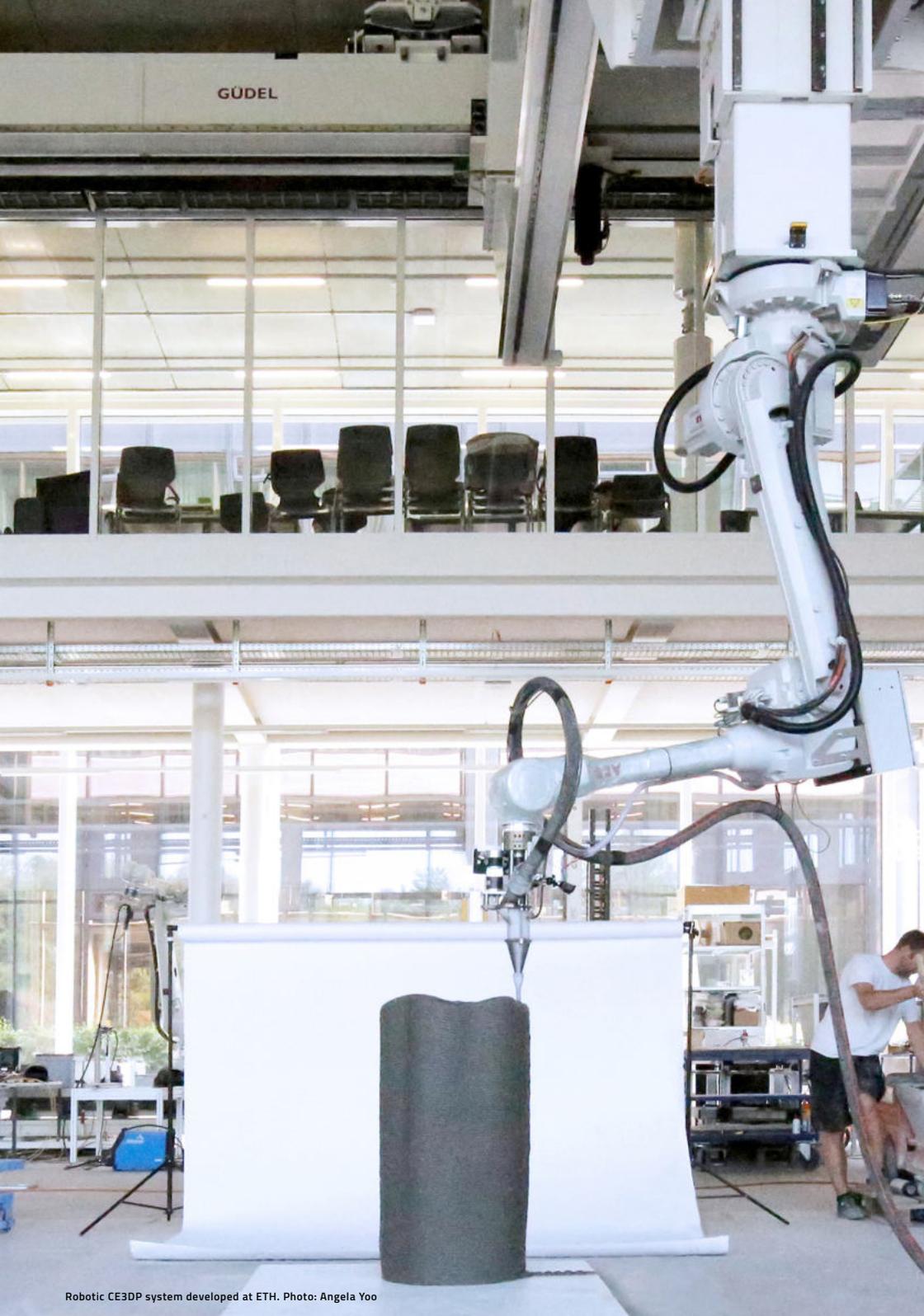
At TU Darmstadt these new structures are numerically developed with the help of topology optimization and capacity load calculation. In the

next step, the elements are additively manufactured and tested. A great challenge here is the finding of suitable process parameters. The parameters such as the settings on the welding machine (current, voltage, wire feed speed, etc.) and on the robot (travel speed) influence the geometry and the material properties very much.

Another advantage of Additive Manufacturing lies in the improved production logistics. The connection elements can be applied directly to the steel beam. This simplifies the production chain of the connection elements: steel plates for stiffeners, head plates, etc. are not needed any more. This reduces material handling, transport and storage.

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INTERDISCIPLINARITY IN CONCRETE EXTRUSION 3D PRINTING A CONCRETE STRUCTURES AND BRIDGE DESIGN

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Abstract

Research into digital fabrication with concrete is advancing at a fast pace, however, these advancements are hardly translated into real constructions. An exponent of recent developments of digital concrete is 3D printing using extrusion processes. This is an additive manufacturing technique where layers of fresh paste are successively placed to replicate a digitally designed 3D model. Professionals from many fields, like architects, material scientists, structural engineers, roboticists and mechanical engineers, are involved in the research and advancement of such a technology. Following material, structural and design aspects, this paper presents the interdisciplinary research entailed for the reliable development of CE3DP.

Digital fabrication with concrete

Fueled by the need to increase productivity [1], digital fabrication in architecture is gaining momentum. Investigated both in academia and industry, digital fabrication is driven by the promise to achieve: customized complex geometries at no extra cost, environmental footprint minimization, automation and improved workers' safety. Because concrete is the most used construction material in the world [2], even a small efficiency boost, ensured by automated production, can have a considerable impact. Being under development,

digital fabrication with concrete has reported many advancements, seen in processes like Contour Crafting (Figure 1.a), powder-bed 3DP (Figure 1.b), shotcrete 3DP (Figure 1.c), slip forming (Figure 1.d) and Mesh Mould (Figure 1.e) [3-6].

Shaping concrete without the use of any formwork offers unrivaled material optimization opportunities. Customization stimulates innovation in geometric design, complex structural forms create more slender concrete structures and removing the formwork reduces waste. However, without formwork a series of new material- and process- specific challenges arise, since concrete has to be shaped before it starts hardening. Concrete exhibits a complex flow behavior and, during placing, has to sustain its own weight. Working, in a digitally driven processes, directly with the fresh concrete entails having both material and process under control. Therefore, all intermediate steps directly interacting with the fresh concrete, like reinforcement, surface finish and quality assessment should be part of the process as well. The complexity of unifying these actions into one coherent chain can be the reason for a relatively slow transition to the real constructions. In this context, critical questions arise:



Figure 1. Digital fabrication with concrete: [a] Contour Crafting, Behrokh Khoshnevis; [b] powder-bed printing, D-Shape, Enrico Dini; [c] shotcrete 3D Printing, TU Braunschweig; [d] slip forming, Smart Dynamic Casting, ETH Zurich; [e] Mesh Mould, ETH Zurich.

- How does the process work in a reliable and predictable way? What hardware and software needs to be developed?
- What are the material properties of concrete during fabrication?
- What are the structural performance, failure mechanisms and long-term durability for the printed material?
- How can reinforcement be added during the process?
- What are the target applications and how to design for the new technique?
- How does digital fabrication impact our building culture?

The above-mentioned processes require specific solutions to these questions. This paper will use Concrete Extrusion 3D Printing (CE3DP) as a case-study to identify the interdisciplinarity aspects made necessary by digital concrete [7], (Figure 2).

Concrete Extrusion 3D Printing

Contour Crafting or CE3DP is an additive manufacturing process where layers of fresh paste are successively placed to replicate a digitally designed 3D model. The process itself was patented by Behrokh Khoshnevis, and in the past 20 years was intensively expanded [3, 8]. As a technology it has the potential to innovate building with concrete because it offers a large design space for architectural applications. Even if most applications focus on printing walls, some prototypes explore other structural elements like columns or bridges. However, the technology is still in its early stages of development and many aspects need to be further addressed to make it reliable and competitive on the construction market.

Material and process

The CE3DP process, an integration between hardware and software, is strategically developed at ETH Zurich as an interdisciplinary collaboration between architects, material scientists, structural engineers, roboticists and mechanical engineers (Figure 2,3). This

system consists of a special printing mortar, working with a set on demand [6, 9] processing strategy and printed robotically. All dedicated hardware is developed to assist existing infrastructure and centralized it into a consistent process. The digital control of pumps and extruder are integrated in the robot controller. Accordingly, the print-tool is mounted on a 6-axis robotic manipulator and material is pumped to it continuously. The work-range of the robot is further extended by hanging it from a 3-axis gantry, on the ceiling. A dormant Portland cement mortar, is pumped to the print-tool where, through active intermixing of additives, the cement hydration is triggered. The activated mortar is deposited onto the print-path and immediately starts to gain structural strength. From the material side, this allows for fast vertical building rates, of 3m vertical height in under an hour [10]. In practical terms, that translates to the structural capacity of the first printed layer of concrete to take the weight of successive concrete layers of concrete, up to a height of 3m without any overhang. Having access to complementary research fields the printing process was developed from scratch in only 18 months.

As previously mentioned, during printing, concrete has to be fluid enough to be pumped but also able to build up strength at a sufficient rate so that it supports the weight of subsequent layers. For this process to make sense in large-scale applications, both printing speed and strength build-up need to be maximized [9,10]. For pumping, an off the shelf industrial device has been selected and integrated with a custom-built extruder able to provide active mixing. The development is a collaborative research effort of architects, material scientists and mechanical engineers. Integrating the infrastructure within the existing robotic facility benefited from robotics and electrical engineering expertise. Furthermore, software development was necessary to enable online communication of motion instructions from computer to robot [11]. These collaborations prove that complex processes can be developed fast, if knowledge is shared.

Hardened concrete, reinforcement and durability

The interface between the concrete layers is one of the key differences to conventionally cast concrete. Due to the inherent weakness of these interfaces in

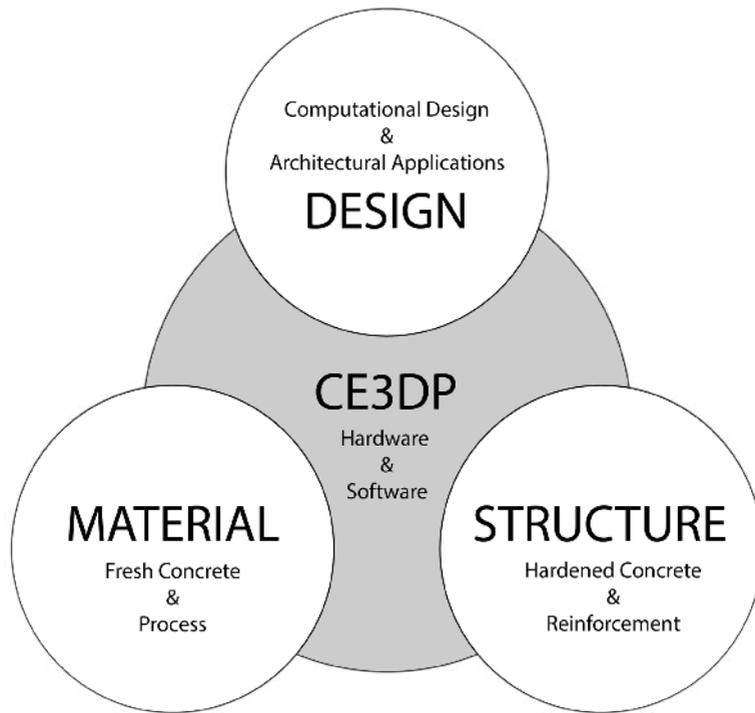


Figure 2. Diagram showing interactions in the development of CE3DP

tension, the structural performance of the material is not isotropic, but depending on the layer orientation.

Each research group or commercial company follows a slightly different printing approach and uses different material recipes. Hence, the material properties during manufacturing and in the hardened state vary depending on the manufacturer.

One of the challenges of CE3DP is the lack of reinforcement strategies suitable for the technology. The concrete tensile strength is typically neglected in the design of conventional concrete structures (only its compressive strength is considered) and the tensile capacity is provided by the reinforcement, which is essential to comply with structural requirements and standards. Currently, most CE3DP processes focus exclusively on the concrete production. Therefore, concrete members build with these technologies

(without reinforcement), do not comply with modern design codes for structural concrete, and their structural performance is much closer to masonry than to reinforced concrete.

During the layered extrusion process, the placement of conventional reinforcement bars hinders the production. Therefore, various attempts were made to find alternative solutions. These solutions include, among others, (i) the use of the printed material as a lost formwork, which is then used as a formwork for conventional reinforced concrete, (ii) the placement of post-tensioning reinforcement to keep the concrete in a state of pure compression and (iii) reinforcing the print material itself, with i.e. either fibers or steel cables [12].

Another issue hindering the development of CE3DP into industrial applications is the compliance with structural concrete standards. The revision of design

codes accounting for the particularities of CE3DP is essential in order for CE3DP to have a significant impact into the construction market. However, this requires a full understanding of the structural performance of reinforced CE3DP members based on testing as well as mechanical models. Unfortunately, little research has been carried out in this direction [13,14] and much further research is still required.

Besides the implementation of reinforcement, the durability of printed concrete is another key issue that received little attention so far. A weak interface could allow corrosive agents such as CO₂ or Chlorides to penetrate the material more easily. The barrier against corrosive agents determines the possibility to use the printed elements as an effective concrete cover for reinforcement. Even if unreinforced, compression-only structures are fabricated, the question of durability is relevant because in the frosting/defrosting cycle, the more porous interfaces between layers can initiate cracks.

The structural performance of the print concrete elements depends on the material properties, on the reinforcement strategy, as well as on the particularities of the printing process. Therefore, any successful solution will require a close collaboration between the different involved disciplines.

Computational design and architectural applications

A method to encourage industrial applications for CE3DP is to identify what types of products can be realized, which justify its use. At the beginning, the technique should focus on highly-specialized, high-value building products, instead of trying to compete with already hyper-optimized conventional concrete technologies.

At present, mandatory conditions for fast construction of conventional concrete structures are: “design discipline, repetition, integration, simplification and standardization of design details” [15]. Hence, any attempt for customization becomes overpriced. This is why customization should bring additional benefits,

impossible to achieve with other technologies. In this context, we search for ways to design concrete elements with new functionalities which can be fabricated in a fully automated factory environment. Hollow elements (Figure 4) can use concrete strategically, only where needed [3], also providing space for integrated water, ventilation and electrical installations. In addition, computationally designed material patterns show remarkable aesthetic potential and durable solutions able to offer alternatives to decorative renders (Figure 4). Another significant added value can be factored at building-scale, for instance, in the case of structural columns, it is possible to gradually modifying the diameter of each element depending on the level inside a building.

A first example of individually printed columns is the recently finished stage installation: Concrete Choreography (Figure 5). Consisting of nine, 2.7m tall elements, each of the columns was individually designed and printed at full height in approximately 2.5 hours. In collaboration with the Origen Festival in Riom, Switzerland, our students from the Master of Advanced Studies in Digital Fabrication and Architecture explored the unique possibilities of CE3DP, demonstrating the potential of computational design and digital fabrication for future construction. This interplay between cutting-edge research and cultural events is a good example of how-to bring technology and novel aesthetics closer to larger audiences.

Conclusion

Many challenges still remain for employing CE3DP at architectural scale: long term behavior, reinforcement, reducing the cement content of the printing mortar, or having a competitive price to conventional methods of fabrication with concrete. Interdisciplinary collaborations are crucial for the development of CE3DP as a viable manufacturing process, as well as for any other digital fabrication method with concrete. Simultaneously tackling these challenges can speed up its transition to a viable technique for conventional construction.



Figure 5. Concrete Choreography. Photo: Benjamin Hofer

Understanding current challenges and limitations, while inventing new ways of building with concrete, will help advance suitable applications that can employ CE3DP for high value products that profit from a digitized concrete industry. This paper also touches upon the fact that technological advancement is not only a matter of the exact sciences. Digitization has an impact on the building culture as well as on its future users. This is why now, more than ever architects are invited to shape the understanding and scale of these phenomena and be prepared to steer this paradigm shift.

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Figure 4. CE3DP column with internal structure. Foto: Keerthana Udaykumar

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MX3D: A 3D METAL PRINTING COMPANY

GIJS VAN DER VELDEN

MX3D

The Dutch company MX3D develops robotic metal 3D print technology. The MX3D proprietary software turns an off-the-shelf robotic arm and a welding machine in an industrial powerhouse.

Creative projects are used to develop critical knowhow by doing. The bronze Butterfly Screen by Joris Laarman led to the ability to print a Marine Shipping Propeller. Other R&D projects enabled the company to 3D print a fully functional piece of infrastructure: the 3D printed Bridge for the city center of Amsterdam.

MX3D has become a technology provider for several industrial parties that are entering the market for large scale metal printing. The MX3D 'Metal XL' Software will be available to selected 3rd parties from november 2019 onwards.

At FormNext 2019 the company not only presents its software but also recent projects like a 3D printed Robotic Arm and Aluminum Bike. At the BE-AM area MX3D presents a bridge handrail study.

Fast Forward a few months from BE-AM 2019 Press Release:

Amsterdam, Februari 2020 – Amsterdam based startup MX3D has placed its 3D printed stainless steel bridge on its final location.

Like all innovative projects the MX3D bridge project required several pivots. The initial tree-like design for the 12 meter metre bridge presented in 2015 has changed significantly. Based on material research and structural testing the team created a new structural design strategy. This led to the final bridge design in early 2017.

The Bridge, designed by Joris Laarman Lab, with Arup as lead engineering partner is installed at its final location.

And with that the iconic project enters a new phase. In addition to its unique construction, the bridge is also a living laboratory for data scientists. It is instrumented by Autodesk, Force Technology, Imperial College London, Lenovo & HBM with an innovative sensor network. Data obtained from the sensors visualize intelligence about



MX3D Printed Bridge 2018_2 photo by Thijs Wolzak

bridge traffic, structural integrity, and the surrounding neighborhood and environment.

These sensors will collect structural measurements such as strain, rotation, load, displacement and vibration, and will measure environmental factors such as air quality and temperature, enabling engineers to measure the bridge's health in real time and monitor how it changes over its lifespan. This data will also allow us to "teach" the bridge to understand what is happening on it, how many people are crossing it and how quickly.

The data from the sensors will be used as input for a 'digital twin' of the bridge, a living computer model that will reflect the physical bridge with growing accuracy in real time as the data comes in. The performance and behaviour of the physical bridge can be tested against its digital twin, which will provide valuable insights to inform designs for future 3D printed metallic structures and ensures it is safe for pedestrians under all conditions.

During the Dutch Design Week October 2018 visitors have been invited to walk over the bridge to generate the first data set. Data from the bridge will be used by partners like The Alan Turing Institute, the UK's national institute for data science and artificial intelligence to build a digital twin model and sensor network which use advanced data analysis to monitor the bridge's performance in real-time. The work on this 3D printed bridge will contribute to the future of safe, efficient and data-driven engineering by monitoring the structure as thousands of people and bicycles traverse the bridge hourly once in place.

Imperial College London researchers have performed a successful static load test of 20 ton in September 2019 at TU Twente. They also tested the maximum possible load by filling the bridge completely with volunteers. Their collective static load was 7 tons.

PARTNERS

The MX3D project has only been made possible through the close collaboration with partners Autodesk, Heijmans, Joris Laarman Lab and ArcelorMittal and the support of Lead Structural Engineer Arup, The Alan Turing Institute Data Centric Engineering Programme, Lloyds Register Foundation, Air Liquide, ABB Robotics.

The public partners are TU Delft, Imperial College London, AMS Institute (Amsterdam Institute for Advanced Metropolitan Solutions) and the Municipality of Amsterdam.

MX3D Key Prizes

The Bridge, designed by Joris Laarman Lab, was awarded several prestigious prizes this year. The Project received the 2018 STARTS Prize from the European Commission for the best Arts and Technology project, chosen out of 2300+ project worldwide. The project also received a Dutch Design Award & the 3D Printing Challenge award

Visit: www.mx3d.com or our youtube channel for more information.

FACTSHEET Bridge

Location Bridge from Februari 2020: Oudezijds Achterburgwal, at the crossing with the Stooftsteeg located in the Red Light District of Amsterdam, Printing Time: March 2017 - March 2018 (effectively 6 months dayshift with 4 robots) Technology: MX3D, Proprietary Software Client: City of Amsterdam Designer: Joris Laarman Lab Lead Structural Engineer: Arup Material & Structural Analysis: Imperial College London Material Expert: ArcelorMittal Research: AMS-3D Building Fieldlab, Amsterdam Institute for Advanced Metropolitan Solutions Digital Tools: Autodesk Digital Twin: Alan Turing Institute

Sensor Network Design & Install: Force Technology & Autodesk Scanning: Faro Technologies Construction Expert: Heijmans & Mous Hardware, computing: Lenovo Hardware, robotics: ABB Hardware, Sensor Network: HBM Hardware, welding: Oerlikon Hardware, air cleaning: Plymovent Welding Gas: Air Liquide Material: Stainless Steel Length: 12.2 meter Width: 6.3 meter Height: 2.1 meter









COMPUTATIONAL DESIGN METHODS DERIVED BY NATURE WITH ADDITIVE MANUFACTURING FOR ARCHITECTURAL DESIGN APPLICATIONS

OLIVER TESSIN
Studio Tessin & 3F Studio

Abstract

Established architectural design and construction methods typically result in material strategies which miss out on morphological material capacities and later deem materials to be down-cycled, creating discord with our natural environment.

Concerning this, the here described approach and methods offer computational design strategies derived by nature to give answers on how to use additive manufacturing in an informed manner to achieve different material strategies.

Driven by this proposed design strategy, the building facade application Fluid Morphology, in development by the spin-off of the TU Munich 3F Studio, founded by Moritz Mungenast, Oliver Tessin and Luc Morroni and the architectural design application Cellular Lattice developed by Oliver Tessin with Bruno Knychalla (Fit AG) may steer a re-thinking towards closed material economy strategies and a novel notion of architectural design

Research Problem

The current growth of our build environment will face shortages of building materials. The building industry usually requires, due to many planning agencies, construction parties and fabrication process steps, high efforts and has many sources of failure.

Established construction methods focus on cost-effective fabrication, often using building elements that cannot be re-used and material mixtures that can only be down-cycling. Even the production processes for those materials themselves e.x. concrete is very energy-intensive and subtractive fabrication techniques waste material. Another cause may be found in our architectural design thinking, which is based on engineered materials for pre-conceived geometrically-simplified forms.

Research Solution - Approach and Methods

Here, an architectural and general design re-thinking towards a more sustainable relationship of natural and human environments is proposed using computation and additive manufacturing to derive design processes from nature's material strategies - evolutionary optimised construction principals. In general and specifically for the following facade application, circular material economies are essential in which building elements are re-used, and materials are fully recyclable if not bio-degradable. In more detail, one of three capacities of the approach are data- and mass computation-driven processes like thermal (energy analysis), structural (FEM), and fabrication simulation

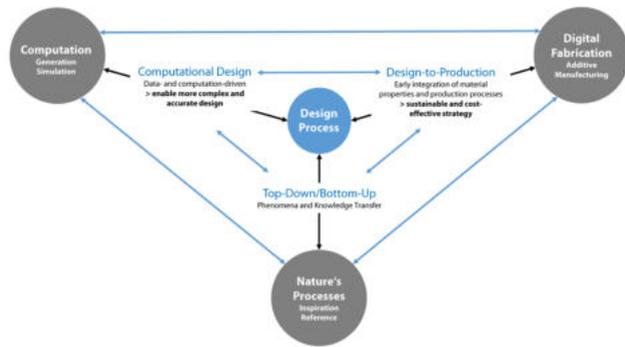


Diagram approach and methods

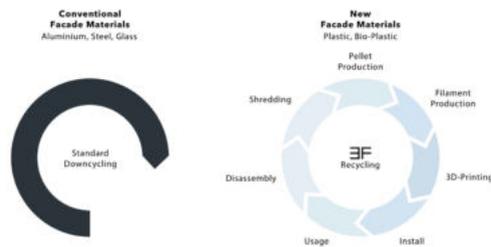


Diagram closed circular material economy compared to standard material solution



Fluid Morphology - Copyright Lehrstuhl für Entwerfen und Gebäudehülle

(Gcode) feed into an evolutionary algorithm to generate and analyse thousands of possible design solutions with pre-defined optimisation goals.

Next, the morphological material capacities of additive manufacturing techniques are integrated early in the design process to enable the high resolution for and the geometrical complexity required by design as well as to decrease the amounts of material needed for fabrication.

The design process looks then into nature's material strategies, but also unrelated phenomena and aims to utilize the 3d printed materials full morphological potential through the generation of geometrically-complex solutions, informed by the functional requirements (external forces) and the materials inherent properties (internal forces) from which - neglecting pre-conceived forms - the fittest design solution emerges.

Performance

The relevance of this design thinking derived by nature can be seen by it facilitating to relate to and to design with nature, instead of against it. Compared to the human brain, the computer-based process can consider more efficiently and accurately the user-defined design requirements and goals, to achieve better performing solutions. Concerning performance measurements, the simulations for the design analysis are already integrated into the process itself. Structural-physical tests provide then the necessary measurements for verification. A general outlook is that visual and constructive aesthetics can create virtually inseparable unities, of which thought-provoking qualities for architectural design arise. The approach creates morphological systems encompassing a limited solution space within which design results can individually be adapted to many different local scenarios.

Research Results

The following two morphological systems are categorised in surface/shell and spatial/grid morphologies. They represent known design and construction problems solved differently, focusing on the approach's key parameter of high resolution and geometrical complexity. The following explanations are structured into form (geometrical design-related) and material (fabrication related) aspects.

Fluid Morphology (surface structure)

Fluid Morphology is the result of the research-oriented studio 3D Envelopes, conducted 2016 with researches and students at the Technical University Munich at the Chair for Architectural Design and Building Envelopes of Prof. Tina Wolf, supervised by Moritz Mungenast and Oliver Tessin. The studio's result

is based on Mungenast's research on multi-functional 3d-printed facade panels, providing the research agenda and on Tessin's research on parametrically smooth folded surfaces involving wrinkle structures.

The morphological system is primarily derived from wrinkle, respectively ripple structures. Both structure types can be categorised to ruga states, which encompass crease and fold structures.

Form aspect

Problem

Building facades consider a multitude of functional requirements like shading, lighting, ventilation, and insulation. Standard facade design solutions solve these into many distinct components, resulting in many processing steps for planning and fabrication.

Solution

Through computational design methods, it is possible to develop for each requirement functional geometric solutions which are computed together respectively integrated into one cohesive facade panel, decreasing the number of components and thus processing steps.

In more detail, the form-adaptive geometric solutions are explained in surface and inner layers. The macro layer integrates architectural functions like seatings and windows. The meso layer is here primarily informed and optimised for self-shading. The angles of the wrinkled surface block sun in the summer, but let the sun pass through in the winter. The microlayer features smaller-scaled ripple structures to diffuse noise reflexion and thus improve acoustics. Following these steps, an inner load-bearing structure is generated functioning as air insulant. Form-adaptive channels can be integrated to provide passive pre-tempered air ventilation.

Performance

The facade system enables to adaptively control the energy input, aimed to reduce building running costs. The simplification through the closed digital chain and the single building element reduces the efforts for planning and fabrication processes as well as sources of failure. Generally, the appearance of building facades is a crucial quality on many levels, and this approach opens up highly customizable and novel forms of representation.

Material aspect

Problem

Usually, through a necessary mixture of materials, facade components can only be down-cycling.

Solution

With 3d printing (Fused-Deposition-Modelling) is possible to fabricate the geometrical solution with only one polymer material (PETg).

Performance

Through 3d printing, it is possible to use more of the polymers malleable morphospace, enabling a general

increase in material performance. The material can be fully recycled 3-4 times - some polymers allow more cycles - and re-used for replacement parts or entirely new panels, creating no extra waste in the process. As all parts are made of the same material - the same coefficient of expansion - assembly and joinery can be simplified, requiring no other construction elements to appear in the envelope.

Project "Interim 3D Printed Facade Deutsches Museum"

The first project planned to be realised with this facade application and the fluid morphological system will be a 750sqm facade for the interim entrance of the Deutsches Museum in Munich in Germany, designed and planned by 3F Studio. The building behind the 3d printed facade is designed and planned by Architekten Schmidt-Schicketanz und Partner with David Wolfertstetter Architektur. The envelope reaches three stories high with a length of 50m, functioning as, coined by the Deutsches Museum, the "gate of the future" for the temporary entrance during the ongoing refurbishment of the museum. Adapted to the architectural program, ticket as well as administrative offices, feature higher fold amplitudes to reduce energy input. Below the Energy Analysis compares a standard flat to the proposed "fluid" 3d printed surface.

Project "Integrated Furniture Wall"

To give a glimpse into the versatility of the morphological system, the following visualisations show an interior wall concept with form-integrated furniture functions. The inner structure is structurally adapted to the load-case scenario, featuring through its low-density transparent qualities.

Cellular Lattice (spatial structure)

Standing 8 meters tall, the so-called retable is the shining new centrepiece of the late gothic church St. Laurentius in Altmühldorf and reflects its future-oriented spirit through the informed use of latest

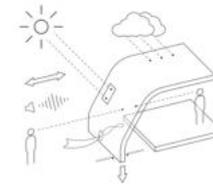
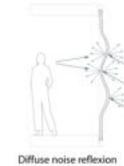
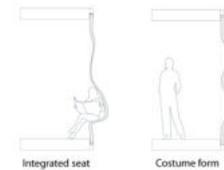


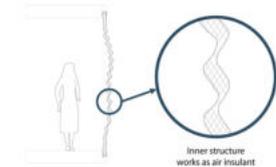
Diagram of functional requirements for building envelopes



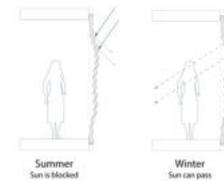
Section diagram microlayer



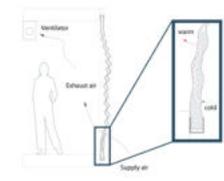
Section diagram macro layer



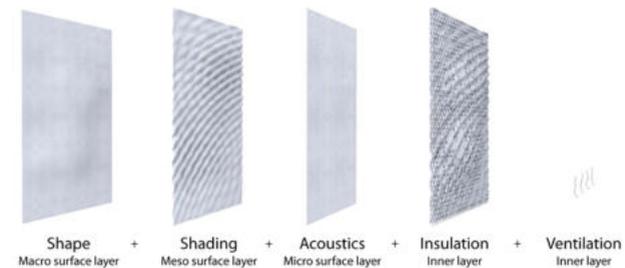
Section diagram inner layer for insulation



Section diagram meso layer



Section diagram inner layer for air ventilation



Perspective diagram of different design and inner layers





Visualisation of the front side with form-integrated bench

technologies, relating to the form-finding strategy of the catenary model.

The Cellular Lattice project is the result of Tessin's research on 3d printed intricate structures, the artist's duo Empfangshalle artistic idea of an 8-meter column-shaped curtain and Bruno Knychalla's, project manager at FIT AG, research on large scale architectural additive manufacturing.

The morphological system is primarily derived from trabecular structure. This type of structure can be categorised by lattice structures encompassing fibrous and sponge-like systems.

Form aspect

Problem

Volumetric geometries e.x. concrete walls waste material as the material structure is solid but structurally not active.

Solution

The cellular lattice system creates an intricate geometry adapting its density to the internal load transmission of the 8m wall object. In detail, the first computer-based process step for generating the structure uses FEM (Finite-Elemente- Methode) to analyse load transmission focused on the left and right sides of the pre-defined volume. Through Topology Optimisation the „digital mass“ of the volume is iteratively reduced until a u-shaped pattern emerges, relating conceptionally to the church's window behind the structure.

In the second step, a point cloud is generated with varying density according to the optimised load transfer in the volume.

Lastly, a line network based on proximity generates the basis for a marching cube meshing algorithm. The meshed node shapes and surface microrelief are structurally optimised for load/weight ratio.

Performance

The morphological system enables light-weight structures to perform in terms of load/weight ratio,

reducing the required raw material and printing time, achieving an intricate aesthetic demonstrating the high-resolution morphospace of powder-bed based additive manufacturing - applicable to virtually any architectural volume.

Material aspect

Problem

Due to the required longevity in the sacral context, the known retardation of 3d printed polymers is an issue.

Solution

To achieve the high resolution required by design, a composite material system of 3d printed polyamide (produced with Selective Laser Sintering EOS P 700 series machines) as the core and wire-arc sprayed aluminium bronze alloy coating as the shell was developed.

Performance

The thickness controlled and structurally active metal coating hinders retardation and results in a globally sound shell with superior performance compared to standard metallization techniques for large scale artefacts, building the required bridge between digital design and realisation.

The contrast between new and old is stark, but the cellular morphological system creates a special bond by relating to the form-finding of its church's gothic architecture, leaving a spectacular but harmonic impression for churchgoers and visitors alike.

This quality may be explained through the increase of consequence of correlation and causation of the form and the material. Both factors computed together in one process enable a mutual dependency of visual and constructive aesthetics creating an inseparable unity on a sand corns level and thus create a unique quality consequent to the formation and materialisation of the artefact.

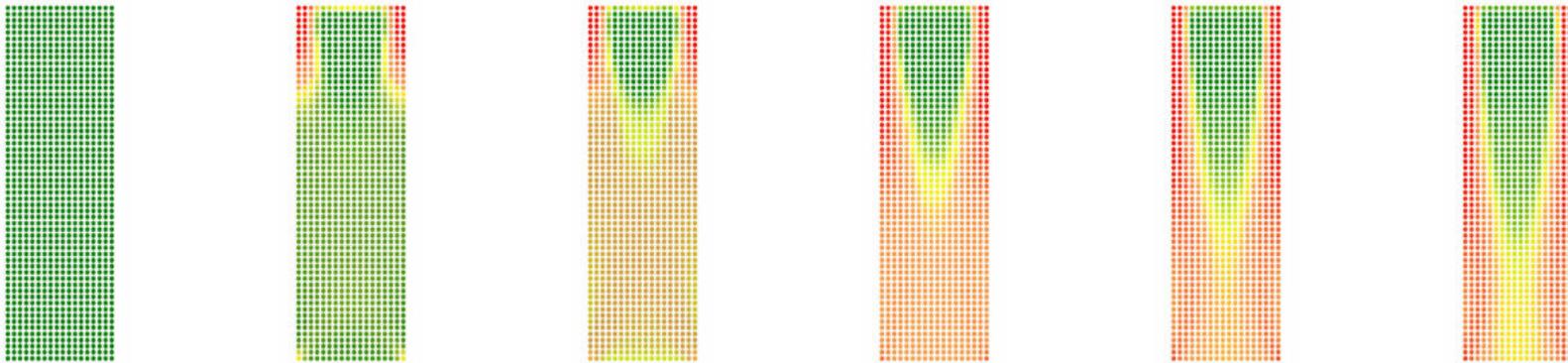


Diagram of iterative topology optimisation steps, indicating from low to high loads with a colour gradient green to red

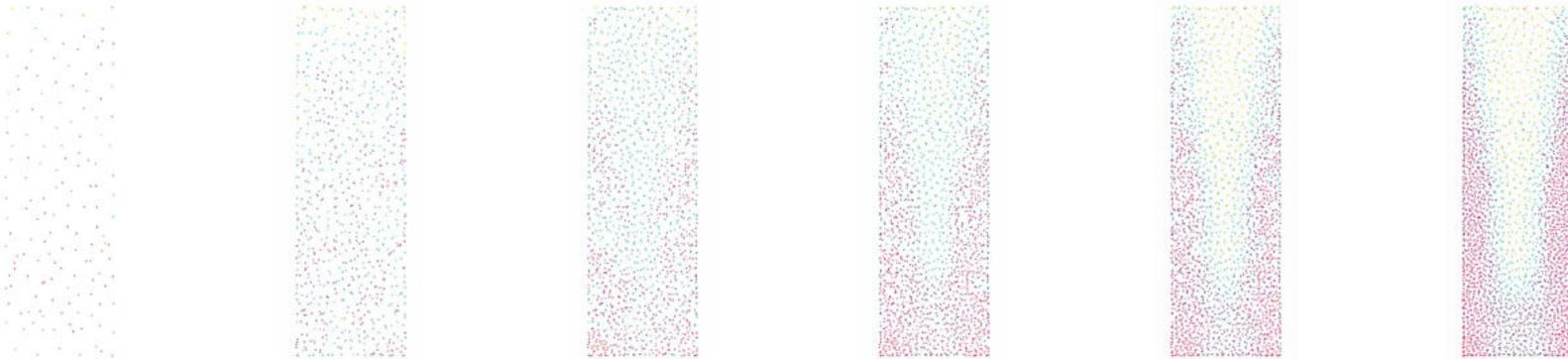


Diagram of generation steps of point cloud according to FEM analysis of topology optimisation result, indicating low to high loads with a colour gradient yellow, green to red

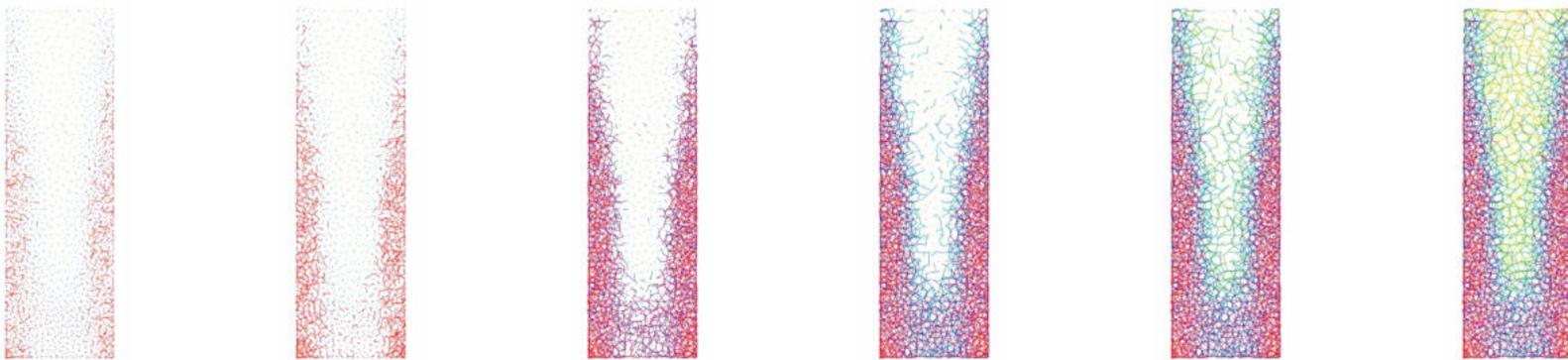


Diagram of the generated line network, indicating low to high loads with a colour gradient yellow, green to red



close up cellular lattice front view

Project “Cellular Column”

To give a glimpse into the versatility of the morphological system, the following photos show the built result of a design study conducted by Oliver Tessin for the Chair of Timber Structures and Building Construction (Klaudius Henke) at the Technical University Munich. The thickness and density of the structure are adapted to a typical load-case scenario.

Outlook

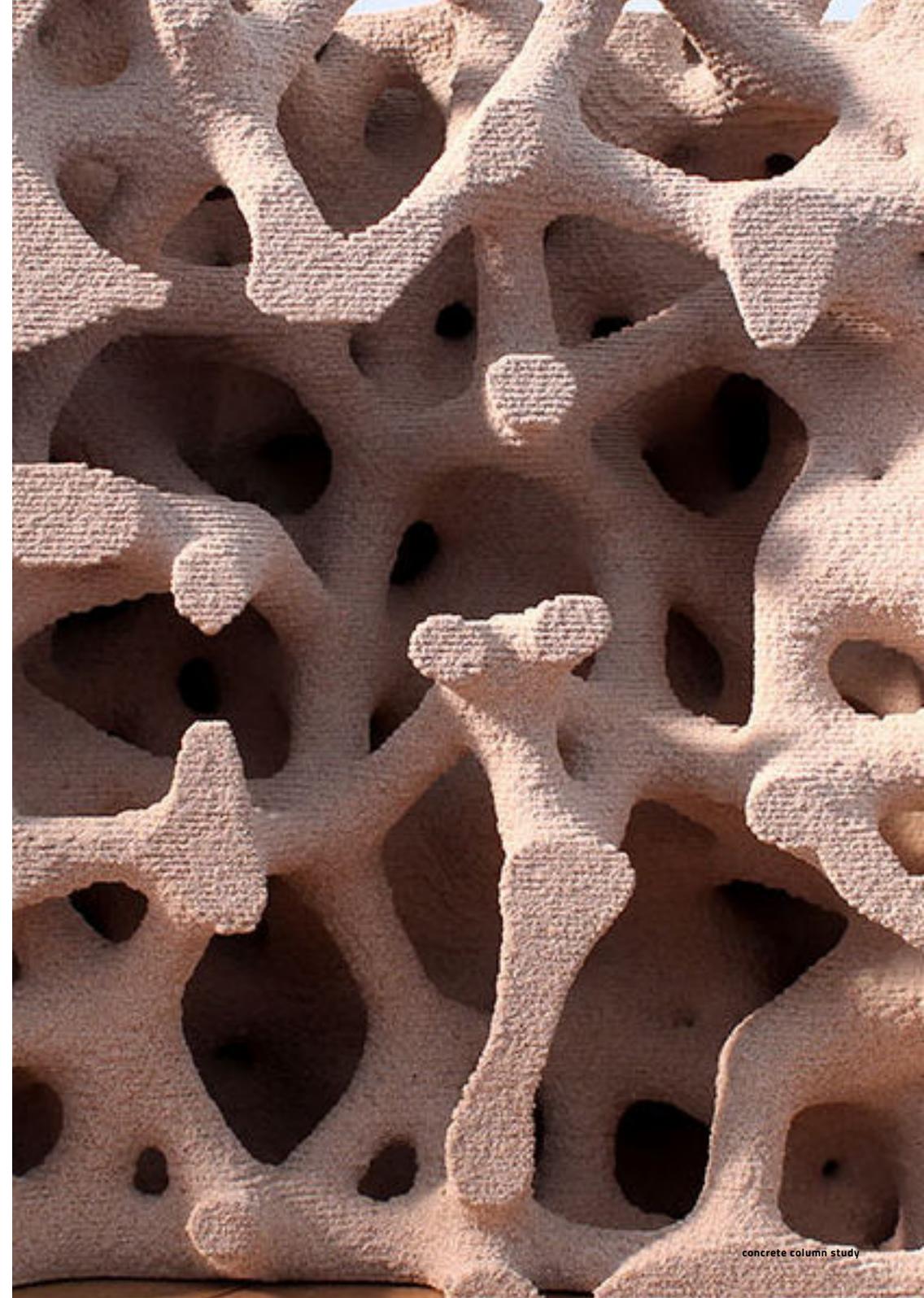
The general above mentioned outlook, concerning visual and constructive aesthetics, is that with this high-resolution fabrication methods one can look deeper into nature's construction principals, which help to understand what our established design thinking and fabrication methods lack, in other words how much we can imagine improving our methods if we'd have nature's construction resolution on the molecular level. The outlook of this potential of detail can help to direct the development of architectural design. For instance, to develop fabrication methods enabling to design buildings on the micro material level.

Fluid Morphology

Potential further developments, beyond recycled polymers – already used in other prototypes - are polymers based on algae and chitin, which are of primary concern to achieve an even more sustainable material economy. Related to the 3d printed materials malleability is the possibility of form-integrating constructive fixtures, from the facades sub-structure directly into the 3d printed panel - no additional joinery necessary. This aspect was developed for the Deutsches Museum project - not shown here. Regarding the design, a multitude of ruga pattern - already developed for other projects - give plentiful opportunities.

Cellular Lattice

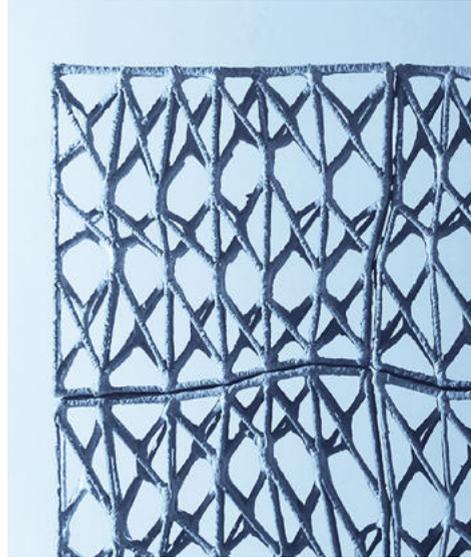
Potential further use of the morphological system, besides large scale metallic artistic artefacts, are load-bearing building elements, using even higher resolution in design. Beyond that, the lattice concept has the potential to be manufactured with WAAM (Wire-Arc-Additive- Manufacturing) technology to achieve load-bearing capacity beyond its weight.



PRACTICE

SOLIQUID

Soliquid
Amaury Thomas
www.soliquid.io



Soliquid is a French startup that has developed a unique 3D printing technology. Instead of depositing the material layer by layer on a tray, it extrudes it into a durable and reusable gel matrix using a 6-axis robot. The young company is offering a faster process that makes it possible to design complex parts, while saving material. Also, no printing support is necessary because it is the gel that holds the part whilst the material is being extruded.



STONE 3D PRINTING

CONCR3DE
Eric Geboers
www.concr3de.com



CONCR3DE offers stone 3D printing solutions to architects, designers and contractors. We print high end finishes, objects and structural elements using waste streams from the granite, marble and travertine industry. Examples are furniture pieces, panels, letterings and logos as well as prototypes, ornaments, columns and walls. With CONCR3DE's technology designers can reduce cost for complex elements, integrate new functions such as sensor technology and piping systems, and create through in a digital, sustainable and waste free process.

The printed parts are durable to the outdoors and mechanically similar to other stone materials. We are scaling up the process and look forward to collaborating with builders, designers and creators.



MX3D HANDRAIL

MX3D
Gijs van der Velden
www.mx3d.com



The piece on display is a test print of the handrail for an earlier design of the MX3D Bridge.

The bridge contains 6000 Kg of 3D printed stainless steel. After acing its final 20 ton load test in October 2019, placement is now expected Q1 of 2020.

With a deposit rate of 2Kg per hour and a deviation of maximum 0,5mm this part shows the potential of technology used by MX3D. Since the mainstream introduction by MX3D in 2015 Robotic Wire Arc Additive Manufacturing (WAAM) is now recognized as the most promising technology for large scale 3D metal printing.



3D PRINTED SMART JOINT SYSTEM

3DPRIYOL
Seungkyu Yoo
www.3dpriyol.com



The South Korean construction 3D printing manufacturer 3DPRIYOL, group of experts in Architecture, has perfected luxury department store designed by OMA. This 13-story building with total ground area of 150,000m2 will open next January.

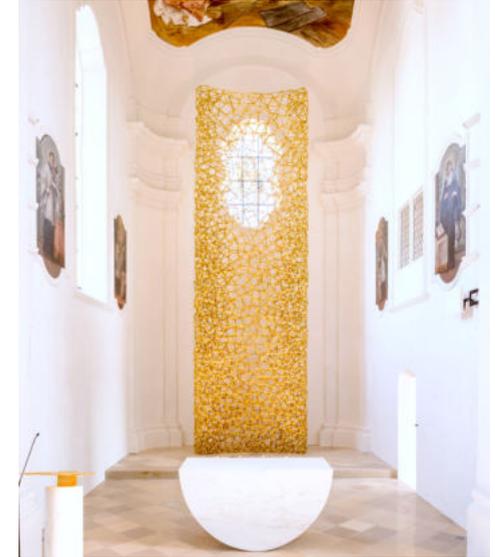
The 3D printed Smart Joint System has been chosen to realize world's first commercial free-form curtain wall as it has solved expensive, time-consuming and unrefined traditional manufacturing system's problem. 3D printing was especially the key to solve its geometric problem - polygonal mesh face-offsetting problem.

3DPRIYOL & WithWorks have jointly designed and engineered non-repetitive 647 smart joints for the curtain wall of 4,600m2 according to the shape of curtain wall.

3DPRIYOL has also adapted both existing manufacturing technology (Iron casting) and additive manufacturing technology (Binder jetting).

AECTUAL FLOOR & ROOM DIVIDERS

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THE CELLULAR RETABLE SCULPTURE OF ST. LAURENTIUS

Studio Tessin
Oliver Tessin
www.studiotessin.com

Aectual is founded out of a mission to bring freedom of design & tailor made architecture to the masses and to make the production of cities cleaner, faster and better

Our dream is to give everyone in the world access to good architecture and sustainable cities. That's why we 'crunch' the complex supply chains of the building industry, by developing digitally produced building products. We're creating actual design freedom, massive cost reduction, perfect consumer quality and no waste. Join this revolution!

Standing 8 meters tall, this architectural artefact is the shining new centrepiece of the late gothic church of Altmühlendorf. Its lattice and prior research on 3D-printed intricate structures aim through computational design methods derived by trabecular bone structure to explore the new potentials of latest additive manufacturing technologies with an unseen resolution for large scale artefacts.

This project is the result of Tessin's research on 3d printed intricate structures, the artist's duo Empfangshalle artistical idea of an 8-meter column-shaped curtain and Bruno Knychalla's, project manager at FIT AG, research on large scale architectural additive manufacturing.

The lattice concept creates a high structural performance by efficiently adapting its density to internal load transmission. To achieve than the resolution that is required

by design, a composite material system of 3d printed polyamide as the core and wire-arc sprayed aluminium bronze alloy coating as the shell was developed, resulting in a globally sound metal shell with superior performance compared to standard metallization technologies. For protection against moisture and the right colouring, a final layer of lacquer is applied for a striking and long-lasting appearance.

The contrast between new and old is stark, but the sculpture generated with the lattice concept creates a special bond by relating to the form-finding of its church's gothic architecture and leaves a spectacular but harmonic impression for churchgoers and visitors alike. Different to the gothic form-finding the mutual dependency between visual and constructive aesthetics is increased, creating an inseparable unity.

3D CONCRETE PRINTING

PERI GmbH
Dr. Fabian Meyer-Brötz
www.peri.de



The construction industry has not seen an increase in productivity in the last decades – in contrast to most other industries. Paired with the global phenomena regarding the lack of adequate housing and the lack of skilled labor this highlights the need for new automated approaches. As such, the technology of 3D concrete printing has emerged at the right time to enable faster and more efficient construction. PERI – a global leader in the formwork and scaffolding sector – together with COBOD – a Danish Start-Up PERI is shareholder of – are hard at work to make the vision of whole houses printed on site a reality.

The present exhibit was printed with the BOD2 – the only second generation concrete printer in the world – to highlight the potential for large structures. Also, using the flexibility of 3D printing not only for design purposes

but also in regard to integration of other building parts – e.g. insulation, electricity and reinforcement – is made obvious by the exhibit. The print material was provided by Italicementi and is characterized as a printable mortar – whereas the BOD2 can also print concrete with an aggregate size of up to 12mm.



The façade node “Nematox II” is the result of the research project of Dr.-Ing. Holger Strauß at the University of Applied Sciences – Hochschule OWL, Germany, together with the Façade Research Group of Prof. Dr.-Ing. Ulrich Knaack at the TU Delft, Netherlands, and the industrial partner Kawneer-Alcoa from 2008 to 2010.

Being the first free form knot, the project proved the potential of Additive Manufacturing (AM) for facade application. The result is the first free-formed aluminum façade node for an existing façade system (Alcoa AA-100 Stick-System). It allows to incorporate geometrical deformation (free-form) of a façade into its digital representation. All necessary accessories of the standard façade-system can be used with no special adaption. The standard profiles connect to the AM nodal points.

NEMATOX II

Lithium Architects GmbH
Dr. Holger Strauß
www.li3architects.com



The 1:1-size prototypes were 3D-printed with a LaserCusing system by ConceptLaser in Aluminum.

The façade node „Nematox II” in its version presented in the dissertation of Dr. Strauß is a genuine rapid prototype. At first, with only little connection to a realistic façade production back in 2010. Nevertheless, it was further developed as a logical consequence of the first development steps with smaller components from a façade system and thus offered a sound basis for its evolution with regard to the digital optimization and simulation of AM components until today.

Note: The presented “Nematox II” is an Alumide copy of the original Aluminum nodes!

COHESION

incremental3d GmbH
Georg Grasser
www.incremental3d.eu



The COHESION Project celebrates the 350-Years Anniversary of the University of Innsbruck.

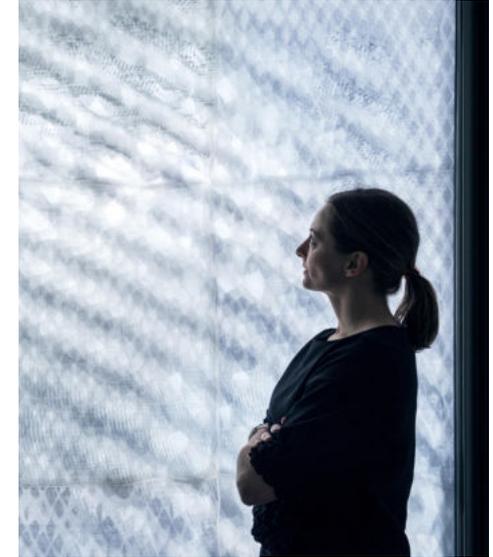
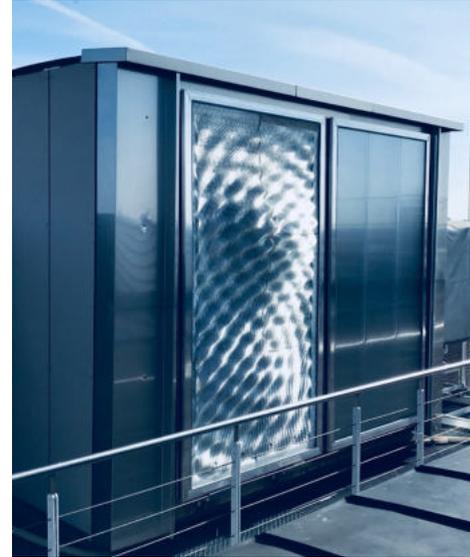
It is the result of a cooperation of researchers and students of the Faculty of Architecture institute for experimental architecture.hochbau and the Faculty of Engineering Sciences Department of Structural Engineering and Material Science Unit of Concrete Structures and Bridge Design. Structural design consultancy was provided by the 3D Concrete Printing research group of Eindhoven University of Technology (NL). The implementation is carried out by the LFUI spin-off incremental 3D GmbH in conjunction with Baumit GmbH and PORR Bau GmbH.

Manufactured in segments by the robot-controlled 3d-concrete-printing-system BauMinator® and partially reinforced by steel and carbon fibers the prefabricated parts

are assembled to create a pavillion as a place to linger as well as a technology platform for all faculties and departments situated at the Technical Campus of the University of Innsbruck.

FLUID MORPHOLOGY - 3D PRINTED AND MULTIFUNCTIONAL FACADE

3F Studio & TU München
Moritz Mungengast
www.3fstudio.de



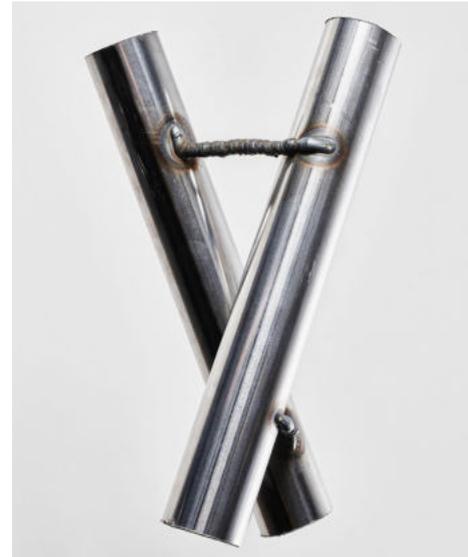
FLUID MORPHOLOGY is the first translucent and multifunctional façade element, which is 3d-printed in one production process. This project shows the potentials of 3d printing for the building industry specially focused on the building envelope. Therefore it describes the closing of the digital chain, by means of the production process from digital design, to planning, to the final product. Yet another major innovation is the 'Functional Integration' of façade functions in this case: sun shading, visual connection, acoustic deflection, load bearing, insulation and ventilation. FLUID MORPHOLOGY combines these functions in one façade element by only using one material, transparent PETG.



RESEARCH

ALGORITHMIC DETAILS

ETH Zurich, Gramazio Kohler Research
Inés Ariza
www.gramaziokohler.arch.ethz.ch



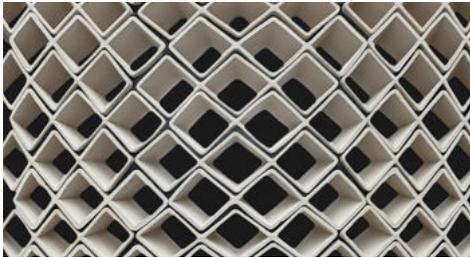
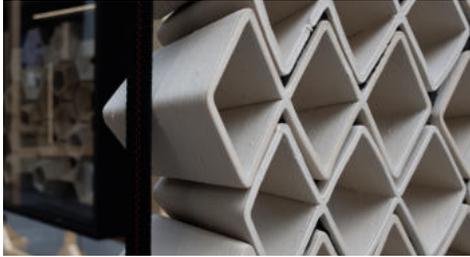
This research introduces a novel construction method that links robotic assembly and in place 3D printing. Rather than producing custom joints in a separate prefabrication process, the algorithmic detailing approach enables the creation of highly specialized connection details that are manufactured directly onto standardized building members during their assembly process. Challenging the current fashion of highly predetermined joints in digital construction, detailing in place offers an adaptive fabrication method, enabling the tailoring of connection details addressing specific architectural conditions.

The algorithmic detailing strategy is explored through robotic wire arc additive manufacturing (WAAM), a metal 3D printing technique based on MIG welding. The robotic process coupled with sensing strategies allows for local

control of the detail geometry enabling the fabrication of connections that can compensate material and construction tolerances. Motivated by increasing new applications of robots for building architectural scale structures, this research aims to contribute with new concepts and methods for adaptive building by enabling the design and fabrication of locally differentiated architectural assemblies.

HIVE WALL

Design Institute of Guimarães, Advanced Ceramics R&D Lab
Prof. Paulo J. S. Cruz
www.aclab-idegui.org



The Advanced Ceramics R&D Lab is an emerging laboratory, based in the Design Institute of Guimarães, which aims to explore the integration of computational tools and additive manufacturing processes in the architectural design and production processes of ceramic elements for building envelopes.

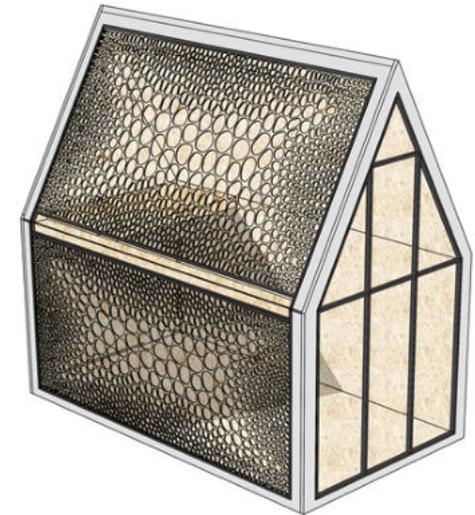
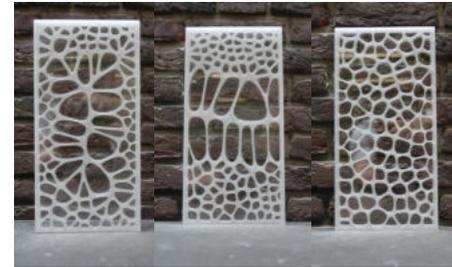
Hive Wall experiments the use of parametric design and additive manufacturing tools to demonstrate the potential of architectural application of ceramic components for facade cladding. The challenge was to define a system for ventilated walls in which the size of the openings are customised allowing wider or narrower openings in accordance to the need of ventilation, shadowing or desired visual constraints. The bricks apertures and geometry are composed by three non-uniform truncated pyramids produced with stoneware.

The assembly is done by horizontal layering that is facilitated by the trimmed formal configuration of the bricks that result in a stable interconnecting and docking system.

The prototype corresponds to a section of approximately one square meter, composed by 56 bricks of 10 cm depth, in which the central point corresponds to the maximum opening of the wall, which progressively decreases towards its limits.

THIN GLASS FAÇADE PANELS WITH 3D-PRINTED CORES

TU Dresden, Institute of Building Construction
Prof. Christian Louter
www.bauko.bau.tu-dresden.de



This project uses high-strength thin glass, that is normally applied on smartphones, and combines it with 3D printed polymer core patterns. The result is an extremely lightweight yet strong and stiff panel that can be applied for façade and roof glazing in the building industry. Compared to traditional glazing a significant weight reduction is obtained, which directly translates into easier installation and less transport energy. Moreover, due to the high flexibility of the thin glass it can be easily bend in architecturally appealing curvatures. For such curved panels the 3D printed core pattern rigidifies the glass panel and keeps it in the desired shape. Besides the structural purpose of the 3D printed core, also sun-shading and daylighting enhancements can be gained from the 3D printed core. This optimizes the comfort of the building user and reduces cooling-energy demands.

The project is a collaboration between Prof. Christian Louter (TU Dresden) and Dr. Michela Turrin (TU Delft) and is supported by AGC. Images shown are taken from MSc thesis projects by Tim Neeskens and Charbel Saleh.

SCAN-PRINT-ASSEMBLE

TU Darmstadt, DDU
Bastian Wibranek & Prof. Oliver Tessmann
www.ddu-research.com



Irregular materials such as unprocessed rocks and wooden branches are currently rarely used in contemporary architectural construction due to the high cost of skilled labor required for preparation. This project investigates methods of graphic statics in combination with technologies such as photogrammetry and 3D printing to build structures from natural reusable building materials. We developed a method for dry-stacking unprocessed rock. We implemented an algorithm to produce 3D printed parts that connect digitized stones in the plane normal to the thrust line. A manually designed input curve is recalculated according to the weights of the objects to generate a compression-only arch.

We employed evolutionary optimization to calculate optimal orientation of digitized stones along the thrust-line. Different stone arrangements and 3D printed connectors were tested. The manual assembly is done using a mixed reality setup. Unprocessed or rubble rock is a massive resource of cheap building material with very low embodied energy that might see a revival through digital technologies.

WIRE BASED ADDITIVE MANUFACTURING OF STEEL HYBRID AND ALUMINIUM STRUCTURES

TU Ilmenau, Production Technology Group
Dr. Jörg Hildebrand
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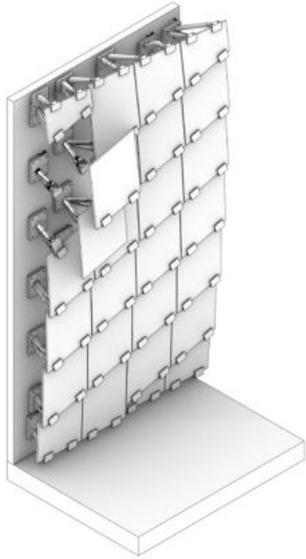


It shows a novel approach for the fabrication of steel hybrid and aluminium structures with wire arc additive manufacturing. The investigations are based on gas metal arc welding technology, enabling build-up rates of 5 kg/h for steel and 1.6 kg/h for aluminium alloy. In the case of the hybrid structures, different steels and / or a rolled semi-finished products and an additive manufactured structural element can be used. As base material low alloyed steel was additively manufactured, whereas FeCrC-alloy was applied as wear resistant functional material.

An example is a tube bend. A joint of pipe is shown of connection between rolled tube cross-section with intersecting struts, which are built up with an additive manufacturing process. The joint structure of aluminum alloys shows the complete fabrication of joint with Wire Arc Additive Manufacturing (WAAM). A correlation of energy input and resulting geometrical features (e.g. layer width, height) as well as microstructural properties was carried out in all cases.

INTERFACES : 3D PRINTED STEEL CONNECTIONS

TU Darmstadt, ISMD & GMSS, imagine computation GmbH, TU Ilmenau, Dipl.-Ing. Hölscher GmbH & Co. KG
Chris Borg Costanzi
www.ismd.tu-darmstadt.de



Additive manufacturing allows the realization of bespoke components with relative ease when compared to many traditional manufacturing techniques. This research utilizes Wire+Arc Additive Manufacturing as a means of producing mass-customized, Steel 3D-Printed façade connections. By introducing 3D scanning in an early stage of the design process, inaccuracies commonly found in façade construction are mitigated through 3D Printed connections. The mockup presented showcases an example of the potential of combining technologies (3D printing and 3D scanning) to more effectively create free-form façade elements.

Collaboration between imagine computation GmbH, Dipl.-Ing. Hölscher GmbH & Co. KG, TU Ilmenau, TU Darmstadt ISM+D & GMSS.

The research project is funded by the "Bundesministerium für Wirtschaft (BMWi)" and „Zentrales Innovationsprogramm Mittelstand (ZIM)" and supported by by Jöckel Innovation Consulting GmbH and the Building Am Network.

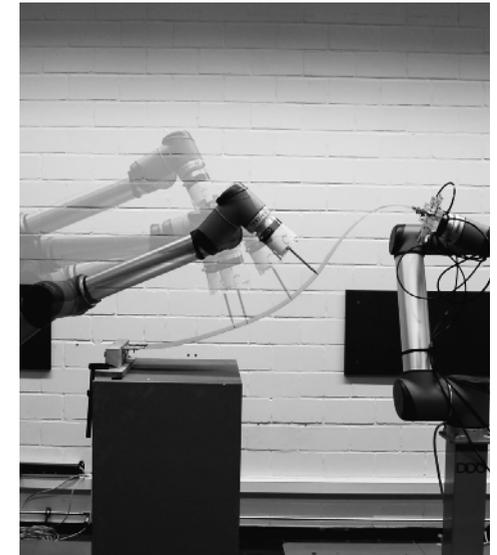
REINFORCING THIN SHEET METAL THROUGH WIRE+ARC ADDITIVE MANUFACTURING

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



This PhD research focuses on the potentials of using Wire+Arc Additive Manufacturing as a means of reinforcing thin-sheet metal. Additive Manufacturing allows for bespoke and novel reinforcement patterns to be printed onto free-form sheet metal, possibly allowing for new architectural expression to be realized. Throughout this research, issues such as warping and deformation of thin sheet material will be mitigated by testing alternative clamping, cooling and welding techniques.

It is believed that this ability to rapidly print bespoke stiffening ribs and connections could find application in the context of free-form facades and structures where, traditionally, otherwise wasteful means of fabrication is used.



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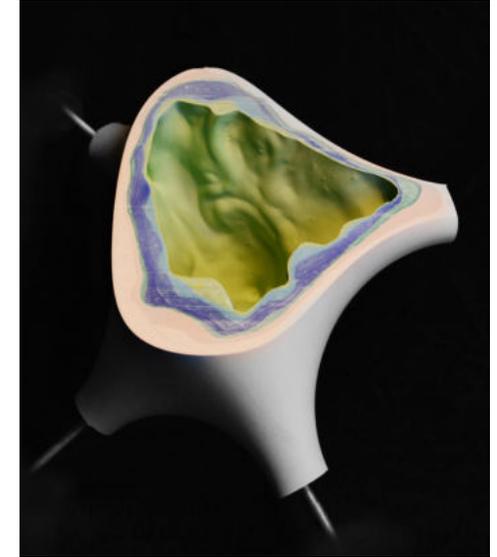
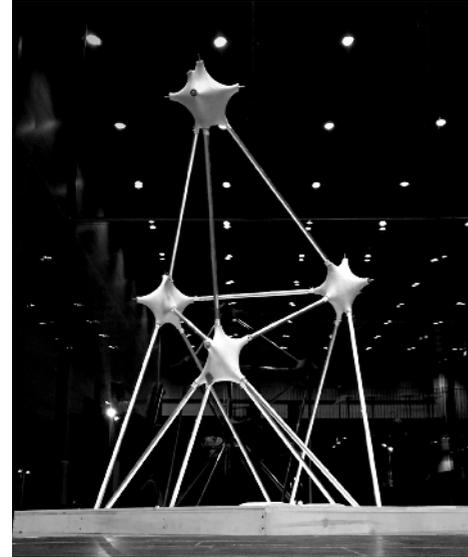
TU Darmstadt, ISMD
Alamir Mohsen
www.building-am.de



ZIM Façade node is a running project guided by TU Darmstadt, and the project partners imagine computation GmbH and Rossmannith GmbH & Co. KG. The project goal is to develop a connection point that targets irregular façade structures within a façade element. The node is digitally designed and additively manufactured. The project investigates new possibilities to generate and manufacture the node. The approach is to generate a node that can ensure the continuity of the drainage level at the profiles. New materials are investigated, such as plastics and concrete. The idea is to 3D print the node in plastics as formwork and fills it with fiber reinforced concrete. A mockup had been built to test the feasibility of the idea. The mockup contains plastic nodes that proved that the nodes could be assembled with different types of profiles. The next step is to test different types of concrete to define the loading capacity of the filled nodes.

ROTO-FORM

TU Darmstadt, DDU
Samim Mehdizadeh & Prof. Oliver Tessmann
www.ddu-research.com



The Digital Design Unit (DDU) rotoforms concrete for resource efficient concrete constructions.

Samim Mehdizadeh from the Digital Design Unit (DDU) of the Technische Universität Darmstadt developed a process for rotoforming concrete elements in a flexible formwork made from hyperelastic membranes. DDU migrated the rotomoulding technology into the realm of concrete casting to produce resource efficient, hollow concrete elements and drastically reduce the waste production of one-off moulds.

Rotomoulding is a production process in which a liquid material is poured into a mould. The amount of material is sufficient to adhere to the wall of the slowly rotating formwork, but not enough to fill the entire mould. The technology is used in the plastics industry for the production of hollow objects such as water tanks, barrels, kayaks,

plastic furniture etc. When used for casting concrete, the small amount of liquid material significantly reduces the hydrostatic pressure that acts on the formwork. The process thus unlocks a completely new range of resource efficient, lightweight formwork materials.

The researchers use reconfigurable jigs in which latex membranes are prestressed into different shapes without the need of cumbersome tailoring. The tensioned membrane forms are minimal surface and withstands the liquid concrete. The resulting concrete objects embody the elegance of concave shapes that are clearly different from the voluptuous results of conventional fabric formwork.

3D PRINTED HOUSES AND BRIDGES

TU Eindhoven, Concrete Structures
Prof. Theo Salet
www.tue.nl



3D Concrete Printing is an additive manufacturing process in which filaments of cementitious mortar are extruded out of a robotically moving nozzle. Although the technology has been pioneered since the end of the 1990's, it has only started rapid growth in the last 5 years. Initially, showcase objects were presented. One of the first actual use projects to be realized with this technology, was the bicycle bridge in Gemert, the Netherlands, which was opened in October 2017. Spanning 6.5 m over a small stream, it features 6 horizontally printed elements that were transported to site, rotated 90 degrees and pressed together by post-tensioning tendons, that provide reinforcement in the longitudinal direction. Reinforcement in the transverse direction was provided by an innovative cable-reinforcement system, developed at the TU Eindhoven. The elements themselves

are hollow with a custom designed infill section to save weight while maintaining load-bearing capacity. To ensure the overall safety and obtain a building permit, an extensive test program was performed based on Annex D (Design by Testing) of the Eurocode. It included custom developed material tests, a 1:2 destructive mock-up test, and an in-situ loading of the bridge before taking it into use.

AM BRIDGE: 3D PRINTED BRIDGE DIRECTLY ON SITE

TU Darmstadt, ISFW & ISMD
Thilo Feucht
www.ismd.tu-darmstadt.de
www.stahlbau.tu-darmstadt.de



The steel bridge was manufactured directly on site by an industrial robotic arm affixed with a Cold Metal Transfer (CMT) welding device. Extensive welding parameter studies were carried out throughout the year, allowing for the bridge to be printed as two independent cantilevered structures which eventually joined in the centre. During the trial phase, the bridge was printed at a 1:10 scale, allowing for the fine-tuning of welding parameters and printing strategies. The production process was further streamlined by utilizing parametric functions as robotic-print paths; drastically reducing the amount of code needed to produce the structure.

This process of horizontal printing makes this a unique structure in the sense that it was printed as one whole and final object. It is hoped that in the future larger spans may also be realized when coupled with moveable robots.

The project was supported by Fronius GmbH, Comau, Messer Group GmbH and WDI.

DRY JOINT COLUMN

TU Braunschweig, ITE
Jeldrik Mainka & Prof. Harald Kloft
www.tu-braunschweig.de/ite/



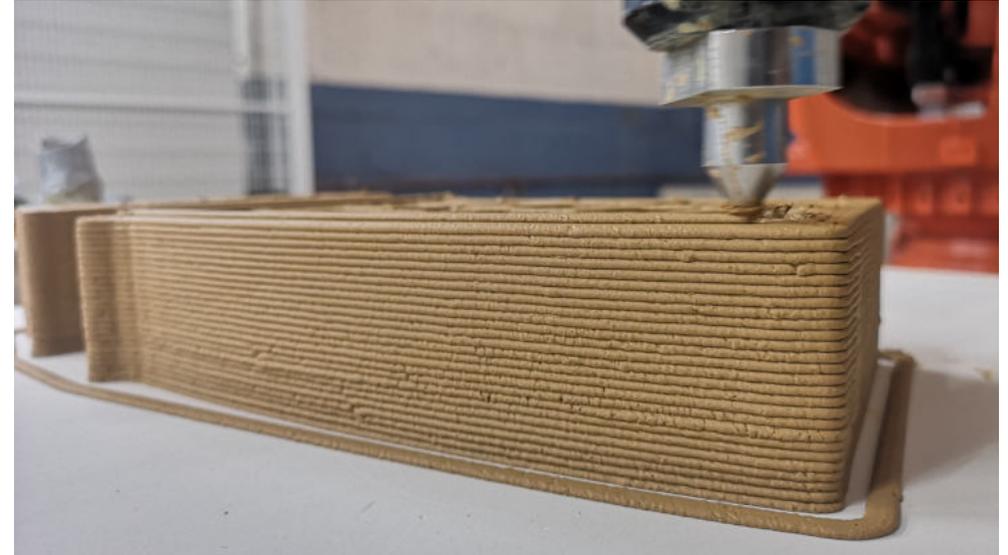
As part of the dry joint column project, the ITE is investigating the potential of 3D printing and precise milling using the full potential of the DBFL. The Shotcrete 3D Printing (SC3DP) process enables a very fast construction of concrete elements. Due to the spraying principle, the relatively large application width and the rough surface appearance, high-precision geometries are difficult to produce. By cutting high-precision dry joints in an additive manufactured element, the ITE tries to combine the advantages of both production techniques in a hybrid production process.



As part of the NTH project for the robot-supported, generative production of complex concrete components, this column was manufactured at the DBFL. It is divided into 4 segments, which are prestressed and joined together by a dry joint and a threaded rod. The support is approx 185 cm high and 70 cm wide. You can find more videos about robot-assisted production on our YouTube Channel.

3D- CLAY BRICKS

TU-Darmstadt ISMD & Unipor
Prof. Ulrich Knaack & Dr. Thomas Fehlhaber
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The research project „3D-printed bricks“ should prove, if its possible to use 3D-printing technology for the production of usable and loadable bricks made out of clay. Especially for the design of bricks, that may not be able to be build in a conventional process like extrusion.

The Project is an ZIM-cooperation between TU-Darmstadt, ISM+D (Institute for Structural Mechanics and Design) lead by Prof. Dr.-Ing. Ulrich Knaack, the UNIPOR Group, Leipfinger/Bader, Ziegelwerk Wenzel and cognition factory.

The 3D-Printer is based on an ABB Robot that is fed with clay from an self developed pump-system. The container can handle 60 Liter of clay in one filling. The Material is pre-pressurized and vacuumized by the container itself. The pumps transport the material with over 15bar of pressure

to the nozzle, where they are printed on an gypsum printbed. The on formnext 2019 presented bricks are part of a wall-design by Dennis DeWitte M.Eng., who mostly developed the 3D-Clayprinter at the TU-Darmstadt. It shows one possible usage of this technique. Because of its characteristics as an insulated material, the wall could now change between outer and inner side of an building without the risk of thermal bridges, this gave complete new options for design.

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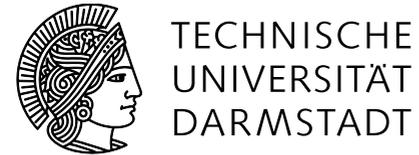
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