

Filigree Vaults

Tales of light and ceramic structure through robotic 3d printing

Authors

Martin Tamke, Henrik Leander Evers (CITA, KADK)

Flemming Tvede Hansen (SuperFormLab, KADK)

Introduction

Digital fabrication technologies allow for mass-customisation of building elements - architectural design shifts from the global repeat of standardised elements to the careful development of localised individual elements. Can this approach be utilized for architectures with spatial ceramic elements?

Filigree Vaults (Fig.1) takes its point of departure in the use of ceramics in architecture. Today ceramic is in buildings mostly used as uniform modular elements for surface application - bricks and tiles. This project discusses and exemplifies new possibilities for ceramics in architecture, which emerge in the interface of traditional ceramic techniques and digital technologies. This novel combination allows for the design of unique ornamental ceramic modules responding to an overall architectural design.

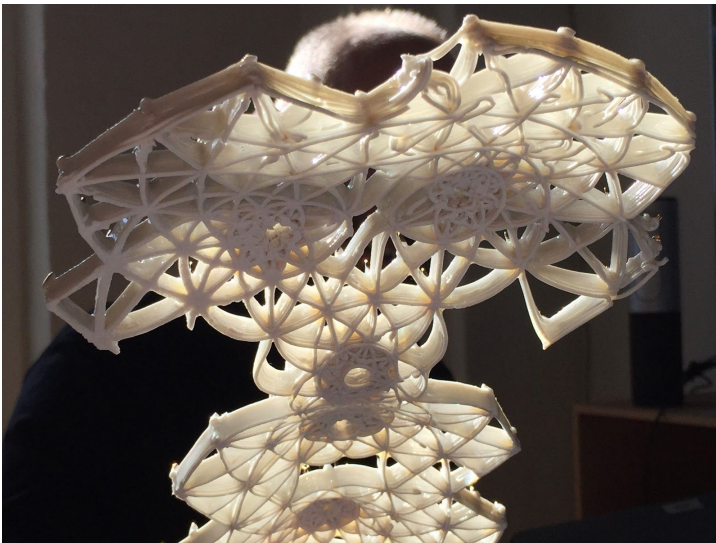


Fig. 1: Porcelain interacts and enhances light and space. testprint of the Filigree project.

Within the broad range of ceramic materials porcelain has outstanding properties. It is characterized by an intensity in surface and texture - this is due to its high content of kaolin. It is kaolin that develops the characteristic white color in porcelain, which is obtained by high temperature firing. The high temperature transforms the material chemically. The porcelain melts but is at the same time able to maintain its shape. It is this property that characterizes the ability of the porcelain to be transparent when illuminated. Likewise, it is this quality that make up the basis for the ceramic glaze to be produced by a special vitreous depth, comparable with the character of a gemstone (Fig. 2).

3D design software and robotic 3D printing allows to highlight and utilise the qualities of porcelain in architectural application. The project speculates on the levels of design, craftsmanship and technology. It asks, how the boundaries of porcelain can be overcome and the material can operate on architectural scale. This investigation is

undertaken in a design lead way, focusing on the building of an architectural archetype: the vault. The project utilises the precision and repeatability of robotic fabrication and introduces the discretisation of overall shape, bespoke patterns and integration of design and fabrication tools. The ornamentation of the vault is steered by the light from the outside. In the exhibition strong light engulfs and penetrates the modules and illustrates the relationship between ornamentation, space, light and shadow.



Fig. 2: The combination of the material depth of porcelain with the precision of 3d printing allows for novel expressions as shown in the lines and spikes, that characterise previous work of the authors.

The project employs an experimental design lead approach and takes place in an interdisciplinary collaboration between CITA: Centre for Information Technology and Architecture, Art Academy of Architecture, Martin Tamke (MT) and Henrik Leander Evers (HLE) and Flemming Tvede Hansen (FTH), SuperFormLab, School of Design.

State of the Art in ceramic 3d print

3d printing with ceramic materials has developed rapidly throughout the last decade in both design and architecture. And in both areas users explored first 3d printers and shift now to robotis as underlying technology for the extrusion of earthen material. In the field of design the point of departure has been the use of desktop printers such as RepRap and Delta 3D printers. Pioneering work was done by the design duo Unfold (<http://unfoldfab.blogspot.fi/>) from Belgium followed by the British ceramicist Jonathan Keep (<http://www.keep-art.co.uk>) and the dutch artist Oliver van Herpt (<http://oliviervanherpt.com>). Working on the scale of pottery they developed the basic technologies principles of translating 3d models into ceramic pieces as well as the potentials, that emerge, when glitches and distortions are seen as positive drivers for design.

Within the field of architecture ceramics are always understood as small parts of a larger assembly. In contrast to other large scale investigations into 3d printing of houses, as in the work on 3d printing with concrete, as done e.g. at Loughborough University (Lim et al. 2011) or D-Shape (Dini 2012), projects in ceramics investigate the potential of modules, texture and stacking. Exemplary work was here done by Building Bytes (<http://buildingbytes.info/>), a research and development project by Brian Peters. He is investigating interlocking modular and stackable bricks printed on desktop 3d printers. IAAC at Barcelona conducts research on the use especially clay as building material (<https://iaac.net/research-projects/large-scale-3d-printing/pylos/>) and tackles as well the challenge of scaling up. This is here conducted through ideas of swarm robotics, where many small robots, build large structures (<http://robots.iaac.net/>). All these projects are constrained by the fact, that they need a perfectly planar surface to start from and massive amounts of supporting structure if overhangs, arches etc are wanted. Work to overcome this limitation uses either an incremental approach, where one layer extends slightly the previous one, or adjustable

molds. The later is pursued by Gramazio Kohler Research at ETH Zurich <http://gramaziokohler.arch.ethz.ch> , where among others physical and digital tools are developed, that manipulate the molding material using an industrial robotic arm.

In common for the above mentioned designers, architects and artist is the ability to develop their printers, robots and printing equipment in their own way to achieve their results of interest. The used digital technologies are open source and encourage to link toolmaking and making as a whole, allowing users to take over ownership of the technologies and develop it in its own right. Working with ceramic materials differs from the general approach to 3d printing, which is characterised by a “fire and forget” mentality. Users are here designing a 3d shape and expect that this digital representation is materialised by the 3d printer. The general approach taken by the state of the art software is here to slice the given shape, define the boundaries, define this as massive printing areas, fill the inner areas with a structural pattern and add support in places, which overhang. This approach is in essence agnostic to properties of material and process and inhibits in consequence a direct application in the field of ceramics, especially when dealing with porcelain.

Our work focuses hence on concepts for the discretisation of an overall composition into modular patterns, secondly the development of support-free 3d printing and the integration of the material properties of porcelain in design and fabrication in respect to ornamentation, transparency, space, light and shadow.

Method and Approach

Design is in our research project used as a method of inquiry, a reflective practice, in which the designer engages. Design inquiries are here used as a method and at the same time, a material practice and a contribution to the production of knowledge(Koskinen, Binder, and Redström 2008)(Brandt, Bernd, and Binder 2007). Design is for this purpose a powerful form of experimentation: a means for inquiring and of producing knowing(Binder and Redström 2006). “It is concerned with moving away from the existing and the known, through intentional actions to arrive at an as yet unknown, but desired, outcome”(Downton 2003). The mean to do enter and engage the unknown were a set of consecutive experiments conducted in the two prerunner projects to the work exhibited at WorkdWorks: Sensitive Ceramics (Hansen, Evers, and Tamke 2015) and Filigree Robotics (Tamke et al. 2016) . The experimentation with material and 3d printing technology led finally to the development of design and fabrication concepts, tools and processes for robotic additive manufacturing of filigree ceramic structures (Fig. 3). This now present technology and knowledge provides the jumpboard for the further research and transfer into architectural scale presented here.



Fig. 3: Robotic 3d printing with porcelain in the Filigree Robotic project.

Design

The project is based on a conceptual framework, that allows for constant evaluation of progress and guides design decisions. We use the architectural type of a Vault as point of departure. Vaults are traditionally compression only solid structures made cut and assembled discrete elements, such as stone, or cast in concrete. Common to these structures is however, that the material is in reality not equally utilised by forces. A fact, which was first used in the Gothic period, when a better understanding of the tectonics allowed to take out parts of the unused material and allowed finally for more elegant and filigree structures. Novel types of structures and surfaces emerged, where tectonic needs were used for spatial design and expression, as in the vaults (Fig. 4) and window openings of the late gothic period. These western examples inspire our work as well as those from islamic culture (Fig. 5 and 6). Where these ornaments are already rulebased it is computation, that allows for a parametric generation of mass customised structures and finally a coupling of these with structural and other performances (Kolarevic and Malkawi 2005).



Fig. 4: Gothic vaults in the Oxford Divinity School (photo: Joanna Penn, Flickr CC)



Fig. 5: Light regulation and shadow play in arabic windows (photo: Seler - Seler, Flickr CC)



Fig. 6: Vault In the Alhambra, Toledo I (photo: Justis Hayes, Flickr CC)

The final framework for the design and fabrication examines the relationship between tectonics and decoration with emphasis on craftsmanship and material quality and consist of three intersecting layers:

1. An arch as global shape
2. modular elements as result of the discretisation of the surface
3. ceramic lines, which constitute the panels; generated as result of an interplay of structural forces and light

This general design framework is further developed in an iterative process between the crafting of the digital environments for design and fabrication and the process of materialisation through 3d printing of clay. The starting point for this project lies within the development of the generative design environment, which is tested and further developed through material experimentation.

Generative Design Development

The shape of the vault is the outset of the generative design process. If provided with a realworld scale the flow and concentration of forces can be analysed with an Finite Element Analysis in the design loop. This understanding of the field of forces on the surface allows us to curate the ceramic print in accordance to the basic structural needs. The size of the kiln at KADK Superformlab provides the second base information, which is the maximum size of the ceramic panels. These two layers of information are used in a custom made algorithm to discretise the surface in as

little as possible panels. The joining areas between these are chosen according to the forcefields and the most stressed parts of the joints are used as outset for the ceramic patterns. These are based on Reothomic surface patterns (Piker 2009), where the defined points provide the seed areas, while the centers of high tension or compression within panels provide the attractor areas for the algorithm. The forces within the surface direct as well the initial generation of printing paths following the surface normals, with more layers positioned in areas of high stress. This placement is altered by a secondary run, where paths and spikes are repositioned in accordance to a light source shining on the material (Fig. 7).

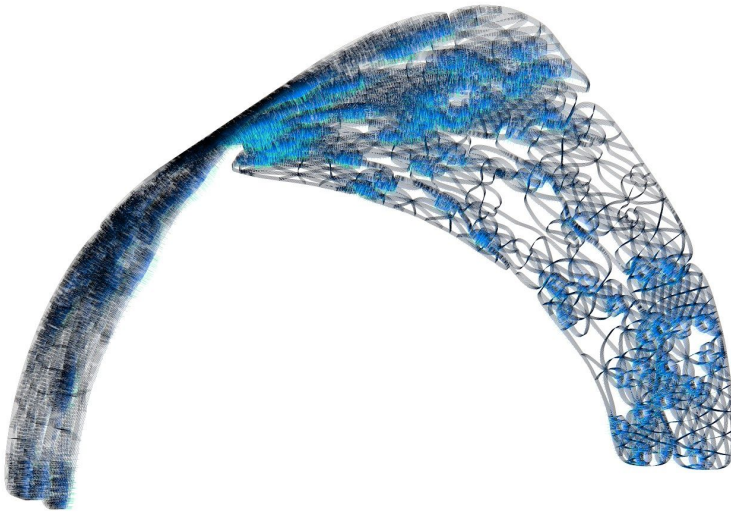


Fig. 7: Overall design of Filigree Vault with discretisation into panels and localised patterns. The black to blue gradient shows the different prin layers.

Fabrication Development

The development of design and fabrication is absolutely interwoven. The pattern generator knows about the limits and constraints of the 3d printing extruder and robot and produces paths, which can be directly fed into them. However the interfaces between the world of design and specification need to be constructed and validated for every project. While design, is inherently based on abstraction and generalisation, the realities of material and its processing are always to scale and include some degree of variability.

Most importantly the project needs to invent a way to print in a rational way without the need for support substructures. We base this process on the work undertaken in the preceding projects. While the focus there was set on individual molds, that are 3d scanned and taken as input for the pattern generation, this project required an approach, which allows for more efficient repeat. For this the classic ceramic techniques of “overforming” is further developed for the use of a robotic 5 Axis for 3D printing with porcelain. This technique is well known in the industry and is found in a variety of versions from simple to complex versions. In “overforming” the ceramic layer is build upon a mold from the same material, separated only through a layer of mineral coating on the mold. This keeps the two structures apart during the process of printing and firing. Here it is of benefit, that both the mold and the object are made of the same material with the same material behaviour during this process.

We use the fact, that the vault has a constant curvature to build a positive mold (Fig. 8), that makes the process of forming of the individual ceramic molds for every printed panel quite efficient.

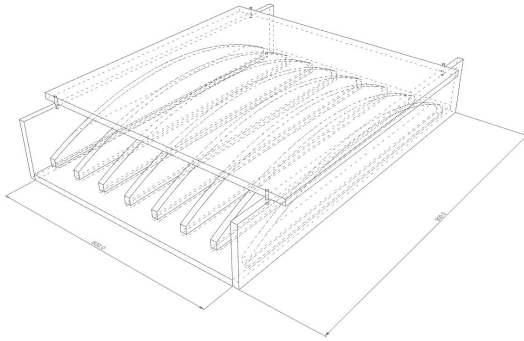


Fig. 8: Construction drawing of the reusable molds for the creation of clay negatives for the process of “overforming”.

Making

The first step in the production is the making of the ceramic negative to print on through the manual rolling of clay and application on the prefab mold. With ceramic feet applied this mold can be flipped. As the material is inevitably exposing behaviour due to drying the shape of the mold is registered with a 3d scanner. The processing of the resulting point cloud allows to detect areas of deviation in the mold (Fig. 9). A feedback into the design environment can be created, where the generated overall shape of the Arc and the panel can be adapted. In this way the workflow becomes aware of material behaviour and the robot's movements fit the physical reality (Fig. 10).

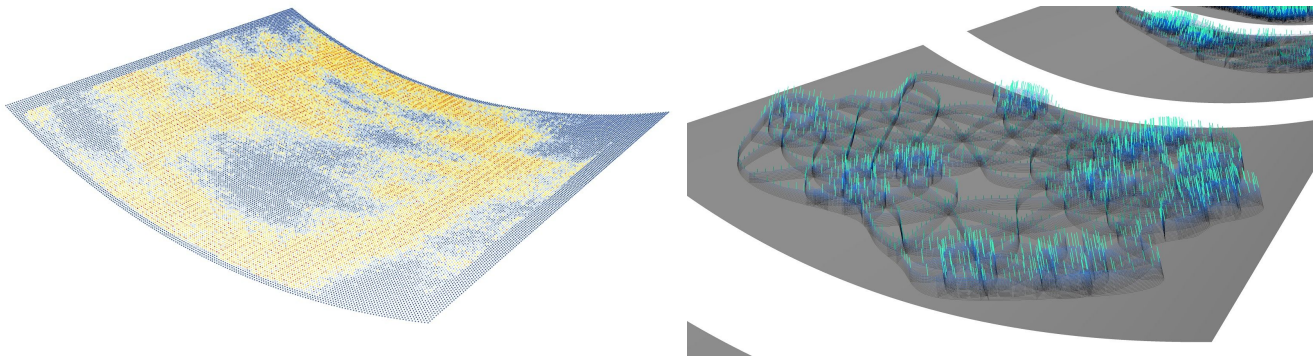


Fig. 9: Deviation of the mold from the design mode. Blue areas deviate more.

Fig. 10: 3d printing pattern on the porcelain moulds (Black to blue lines) and Spikes (turquoise)

The adapted 3d printed paths are driving the robotic movement of the custom made clay extruder at CITA. Based on equipment from medical industry it allows to regulate the precise flow of clay through the 3d printing nozzle. In combination with the control of the robots movement in the 1/10 millimeter the printing of clay can not only be executed with high precision, but as well stopped at any moment. This allows for novel expressions as the 3d print of spikes, which are later glazed with gold. Overall the fine print is able to utilise and emphasise the nature of the porcelain as a plastic material. The prints are characterised by the plasticity and "life" of clay expressed in the layered built. The final step in the making of Filigree Vaults are several steps in glazing and the firing at 1260 degrees. The single panels are assembled using the registration “tooth” at the edges of the panels and mineralic glue. A strong light source shines on and through the modules, illustrating the relationship between material, ornamentation, space, light and shadow.

Conclusion

Through the project, we investigate the customisation of unique ornamental ceramic modules responding to an

overall architectural design in the interface of traditional ceramic techniques and digital technologies. The project speculates on the levels of design, craftsmanship and technology and how the boundaries of porcelain can be overcome and the material can operate on architectural scale.

The shape of a vault is the outset of the generative design process and experimentation with robotic 3d printing of filigree shaped modules. Parametric 3D design software, 3D scanning and robotic 3D printing has allowed us to highlight and utilise the qualities of porcelain in architectural application.

The project combines specialised knowledge in architecture, ceramic art and robotic technology with the desire for experimentation through probes and prototypes. The project provides the basis for further interdisciplinary experimental collaboration in architecture and design scale. The exhibition WorkWords opens the project and approach to the public and allows for the discussion of the future relations of architecture, craftsmanship, design and technology.

Author's biography:

Martin Tamke:

Martin Tamke is Associate Professor at the Centre for Information Technology and Architecture (CITA) in Copenhagen. He is pursuing a design led research on the interface and implications of computational design and its materialization. He joined the newly founded research centre CITA in 2006 and shaped its design based research practice. Projects on new design and fabrication tools for wood and composite production led to a series of digitally fabricated demonstrators that explore an architectural practice engaged with bespoke behaviour. Currently he is involved in the 7th framework project DURAARK and the Danish funded 4 year Complex Modelling research project.

Flemming Tvede Hansen:

Flemming Tvede Hansen is a graduate student from the Danish Design School 1990-95 specialized in ceramics and glass. His Ph.D. Scholar was about integration of digital technology in the field of ceramics and defended in 2010 at The Danish Design School, Copenhagen. His current research is about how experiential knowledge of crafts rooted in ceramics can be transformed and utilized in the use of digital technologies with a focus on involvement of the body. Flemming Tvede Hansen is currently working as a Research Assistant professor, The Royal Danish Academy of Fine Arts - Schools of Architecture, Design and Conservation, Copenhagen, Denmark.

Henrik Leander Evers:

After studies both in Denmark and Mexico and an internship at the R&D department GXN 3XN (gxn.3xn.com), Copenhagen Henrik graduated with a M.Sc. in Architectural Design from Aalborg University in 2011. Since then he has been conducting research in computational strategies in the architectural domain – from algorithmic and parametric design through digital registration technologies to computational approaches in renovation, retrofitting and fabrication – as an architectural research assistant at Centre for Information Technology and Architecture (CITA), The Royal Danish Academy of Fine Arts - Schools of Architecture, Design and Conservation, Copenhagen, Denmark.

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