Support-strategies for Robocasting Ceramic Building Components

Exceeding the geometric limits in printing clay

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The introduction of ceramic additive manufacturing technologies in the building industry offers unprecedented opportunities to architects and engineers towards a new brick-architecture. Robocasting appears as a suitable technology to produce the medium- to large-scale components needed for building applications. This process involves deploying individual strands of clay layerwise to form an object. Unlike powder-bed or sheet-lamination-processes, robocasting does not come with a process-inherent support-material. Using support-material increases the range of producible geometries and therefore is a crucial necessity to exploit the technology. In this paper, first the limits of the unsupported process were identified. Also, a representative architectural component, which included overhangs, bridged areas and arcs was designed generatively. In the first stage, its geometry was derived from the material-related limitations of the used clay. Next, different strategies to exceed the process-related limitations have been developed and tested. The results are discussed and an overview of these counteractions and their applicability is provided. Ultimately, the representative architectural component was fabricated once again, with a geometry exceeding the geometric limitations by applying the support-strategies that were developed beforehand.

Keywords: *Additive Manufacturing, Ceramics, Clay, Robocasting, Support-structures*

INTRODUCTION

Since its introduction in the 1980s (Hull 1984), Additive Manufacturing (AM) technology as a novel way of fabricating complex parts, gained a foothold in all branches of the industry. The term 3D-printing (3DP), often used analogous to AM, hereby actually covers a broad range of different technologies and processes. They all have in common that fabrication is taking place by deploying or bonding material only in places where the model demands for it. By this AM can be described as diametrically opposed to subtractive processes such as milling, where a geometry is carved out of a larger block of material.

As in most of the processes material is deployed layer-by-layer, layer-height has a huge impact on the print's resolution, therefore thin layers are preferred for high surface-qualities. On the downside, AM tends to be a slow process and it is hard to produce big parts with a good surface-quality at reasonable fabrication-times. The construction industry, that by its nature of creating large structures, has an inherent demand for big parts only slowly adapted to this technology. On the other hand, Construction and Architecture in particular, is a sector with a great need for customized solutions, therefore there are great opportunities in the adoption of the AM process-chain (Rosendahl and Wolf 2022).

While in other sectors additively manufactured components are already prevalent on the market, AEC made its first careful steps towards this in recent years. While some approaches tackle the task of producing full buildings like houses (Koshnevis and Hwang 2006) or bridges (Van der Velden 2019), others focus on highly specialized components like façade-connectors (Mohsen 2020), lost formwork (Burger et al. 2020) , fire-protection cladding (Pain 2022) or even hybrid applications (Carvalho, Cruz and Figueiredo 2022). Nowadays, the scope of AM R&D covers most of the materials common in construction such as metal (Erven 2021), concrete (Anton 2020), glass (Seel 2018) and ceramics (de Witte 2022) upon which this article takes a deeper look.

Using fired clay as a building-material dates back to when in ancient Mesopotamia first houses were built from ceramic bricks. As over the centuries other applications like rooftiles, bathroom-ceramics and façade-claddings were developed and nowadays the high relevance of ceramic building-components seem unbroken.

Even though there are manifold ways to additively process ceramic materials (Chen et al. 2019), so far only Robocasting (Cesarano, Segalman and Calvert 1998) has proven to be capable of producing large parts in a reasonable time and is therefore suitable for the building industry (de Witte 2022). According to ATSM F2792-12A, Robocasting is classified as a material-extrusion process. When analyzing the technique, many analogies can be drawn to the FDM process. To fabricate Robocasted parts, individual strands of a clay-paste are deployed line-by-line and layer-by-layer to ultimately form a printed object. Afterwards, the green body is dried and fired to conduct a sintering-process, that gives the components their final stability.

Yet, the AM of ceramic building components is still in its infancy, even though at least 30 projects in this field have been carried out so far (Wolf, Rosendahl and Knaack 2022). Unfortunately, many of these can be seen as proof-of-concept, art and architectural avantgarde, lacking an accessible documentation that may work as a foundation towards further exploration. This article examines one of the unanswered questions regarding the process: the use of support-structures to gain a greater geometrical freedom.

Unlike other AM-processes, Robocasting does not come with a process-inherent support-material to easily enable the fabrication of overhanging or bridging sections in a print. While for example in powder-bed based processes a binding agent is deployed only in desired places, the non-processed powder still works as a scaffolding for such overhanging sections. If, during robocasting, strands of material are deposited in areas that receive no or insufficient support from below, the green body will deform, leading to an unsatisfactory result. In general, deploying strands of clay to support these areas, which is later removed, is possible.

So, without the use of support-structures, robocasted ceramic components are limited to geometries with steep overhangs and short bridges. By investigating strategies to support areas with sloped overhangs and wide bridges, it is aimed to achieve a greater geometric freedom and by this make the process more applicable for all kinds of ceramic building components.

METHODOLOGY AND BOUNDARY CONDITIONS

The experiments in this research have been carried out on a Lutum4-machine, a commercial clay-3D-printer with three degrees of freedom (XYZ-control) and a build volume of 430x460x800mm. The clay-paste is loaded into cartridges and fed to the extruder by air-pressure where it is dosed by a screw. The 3DOF-Layout of the machine is common in many AM processes, allowing the stacking of parallel layers in Z-direction. Systems with a higher degree of freedom, such as six-axis robotic arms, may allow different approaches to handle the problems of overhanging and bridging, but are not prevalent on the market and not in the scope of this research.

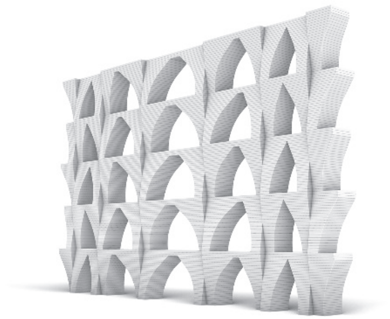
Figure 1
Separating wall-element composed from the illustrative geometries

The specimens were modelled in Rhinoceros3D with the support of the Grasshopper API. To carry out first tests, PrusaSlicer was used for generating G-Code for the printing paths. Later, when it became necessary to gain a higher control of individual printing-paths, G-Codes were created using Grasshopper.

As discussed beforehand, the construction industry has an inherent demand for large components, therefore a wider nozzle with a diameter of 5.2mm, resulting in a strand-width of 5.5mm was used for the fabrication of the specimen. As a best practice known from preceding projects, the recommended layer-height is about 50% of the nozzle diameter. Several tests have been carried out to determine layer-height (cf. Preliminary study on material and geometry) resulting in the decision to mostly work with a height of 2mm.

The clay-mixture used for this research was already proven as suitable for additively manufacturing ceramic building components in previous projects (Cruz et al. 2020). When it comes to printability, one of the most influential parameters of a clay is its plasticity, enabling the viscous mass to pass through the extruder and to be stable enough to be stacked layerwise. Even though there are competing methods to determine a clay's plasticity (de Oliveira Modesto and Bernardin 2008), in this case it was assessed by the Pfefferkorn-Test. The mixture used for this research showed a compressed height of 8mm, resulting in a plasticity-factor of about 5. Nevertheless, clays as natural materials are expected to have properties differing from each other. The used clay only serves as an example and the presented methodology may needs to be adapted to other mixtures as other research carried out on overhang shows (Kontovourkis and Tryfonos 2020).

After printing, the specimens were dried at room-conditions. As soon as the specimen were dried and touchable, the photographic documentation and evaluation was carried out. Before the examination of support-strategies took place, the capability of the material to perform overhangs and bridges has been determined by printing a sample geometry (Fig.2) containing several inclined surfaces and bridges of different lengths.



To depict the limitations of the material, an illustrative architectural geometry was generatively designed (Fig.1), containing inclined surfaces and bridges not exceeding the found values. Afterwards, several strategies to support steeper overhangs and wider bridges were examined. The examined strategies have been evaluated in terms of removability, surface-quality, geometric precision, print-time and processability. Ultimately, the architectural geometry was generatively altered to depict what is achievable by applying the findings.

PRELIMINARY STUDY ON MATERIAL AND GEOMETRY

To identify the material-related limitations of the used clay, a model was designed whose geometry is defined by overhangs of different angles, as well as bridges of different spans. Furthermore, ¼ of a sphere was included to observe, if changes in inclination may cause different effects, as well as to test how arced structures are affected by overhang.

Fig 2 illustrates the model containing overhangs ranging from 7,5° to 60° in increments of 7,5° and bridges ranging from 10mm to 50mm in increments of 10mm. The Diameter of the ¼-sphere was 90mm. To avoid effects caused by neighbouring geometries supporting each other, testing areas have been separated by gaps.

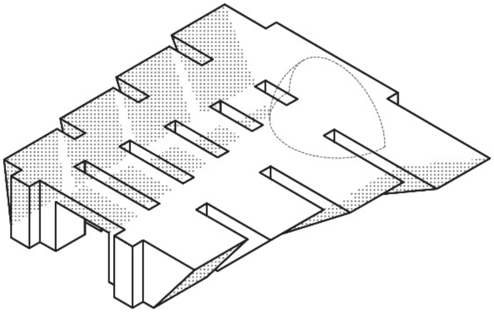


Figure 2
Testing geometry to assess overhang- and bridging abilities

The geometry was printed in different layer-heights to observe the relation between layer-heights and capability to perform bridging. It was expected that smaller layer-heights enable better overhang-abilities, as the "side-steps" to incline turn out smaller. The applied layer-heights were 2mm, 3mm and 4mm. Also, a control specimen printed upside-down was created with a layer-height of 3mm.

It was observed that, reduced layer-height resulted in a slightly better overhanging-capability. While at 4mm layer height the highest inclination providing a satisfactory surface was limited to 30°, a layer-height of 3mm provided acceptable results up to 37,5°, but 2mm did not lead to further improvement (Fig 3). Also, it can be expected that very steep overhangs, even if supported, will result in poor surface-qualities, because "side-steps" will become too big.

Further, it was observed that neither of the layer-heights did significantly improve bridging-ability (Fig.4). In general, free hanging strands of clay appeared to be one of the greatest challenge in this research, as a sagging of the strands was observed even on smallest bridges. Exceeding layer-height only resulted into strands being less prone to tearing apart.

In terms of arches, and respectively domes, results only confirmed the findings from overhangs. Again, a smaller layer-height enabled satisfactory results at slightly to higher inclinations, but steep regions showed effects similar to bridging.

Furthermore, the maximum material output of the machine appeared to be limited. This was observed by comparing the printing time of the 2mm, 3mm and 4mm specimen, which all took about 2:30 hours to print, even though path-length in the 2mm-piece is about twice as long as in the 4mm-piece.

From these preliminary investigations it was concluded that further in this research:

- Printing may take place at 2mm layer-height, as with higher layers no time is saved
- Support is recommended for overhangs of more than 30°
- Inclinations steeper than 52.5° will result in poor surface-quality
- Arcs will not be observed closer, as the results from overhangs and bridges apply
- Any unsupported bridging is impractical, as even smallest spans tend to sag

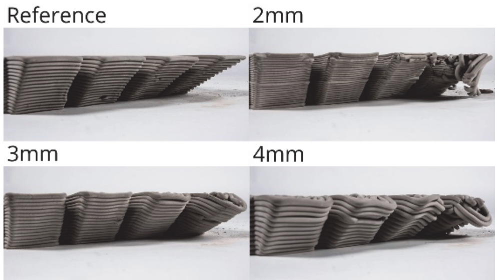


Figure 3
Comparison of overhangs >37,5°

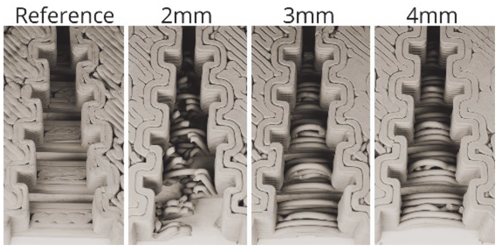


Figure 4
Comparison of bridges

DESIGNING AN ILLUSTRATIVE PIECE

In the following step, an architectural geometry was generatively designed. The pieces cubature is defined by a pointed arch with variable steepness, which's keystone can be extended into a bridge as seen in Fig.4. Considering the findings from before, overhang was set to 30° and bridging to 0mm, to display the materials limitations if no support is used.

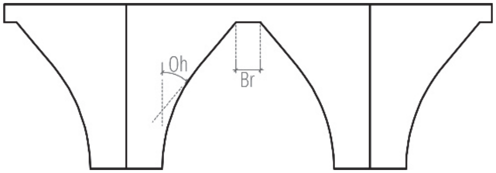


Figure 5
Drawing of the generative geometry with its parameters

Figure 6
Printed illustrative piece with 30° overhang and no bridge

EXPLORING COUNTERACTIONS

To investigate counteractions, two different specimens, one for overhang and one for bridging, were designed and tested independently. The overhang-specimen contained an inclined surface of 52,5°. The bridging-specimen contained a span of 75mm. Both geometries were printed upside-down to serve as a reference for an idealized outcome.

First, the orientation and layout of printed clay-support was investigated. Secondly, the connection in between the print and its support was examined, as it tends to negatively affect the appearance of printed objects. Interface-layers, which prevent the clay-strands from connecting to each other, were expected to improve this. Several different interface-materials, namely foil, oven-paper, XPS-foam, cardboard, spray-oil and printed cellulose-paste were tried for their applicability. Lastly, it appeared to be timesaving to use placed supports from other materials like XPS-foam and cardboard.

Printed support from clay

Overhang. To assess the properties of printed supports from clay for overhangs, two strategies have been examined. First, a set of strands parallel to the supported geometry was created, to provide a linear bearing. In between the prints and their support structure a gap of 1,375 and 2,75mm was left to enable removability. Secondly, a comb-like support-structure perpendicular to the slope, was designed to support pointwise. The distances of the comb-array were set to 2,5mm respectively 4mm.

Support-structures parallel to the overhang showed good removability and satisfactory surfaces. At the distance of 2,75mm (50% strand-width) the specimen only showed small marks on its surface (Fig.7 B), while at 1,375mm (25% strand-width) marks were visible more clearly (Fig.7 A). Regarding the geometric precision, a light sagging of the strands hast been observed, as the material sagged a bit to rest on the supports. On the downside, this method required a large amount of material and a longer printing-time. It showed good processability, as support-structure and print were fabricated alongside.

Both specimens with support-structures printed perpendicular to the overhanging surface showed unsatisfactory results in terms of surface-quality and removability, regardless the comb-distance (Fig.7 C+D). Due to the fact, that at the beginning an extrusion-movement, the nozzle tends to show latency in material -deployment, and also shows overflow at the end of movements, connection-points were often left out or too big. It proved as difficult to differentiate which was part of the support and which was part of the print, leading to unintended breakaway of printed parts. Going hand-in-hand with this, geometric precision was unsatisfactory. The printing-time turned out slightly lower than in parallel orientation, while processability remained similar.

Bridging. To assess the properties of printed supports for bridges, two strategies have been examined. First, massive block was created with a planar surface facing the bridging area. This has been examined once with zero clearance in between the support and the print and again with a 1mm-gap. Secondly, a comb-like support-structure was designed to support pointwise. This also was tested in two iterations: with a distance of 2,5mm in between the supporting walls, as well as with a distance of 4mm.

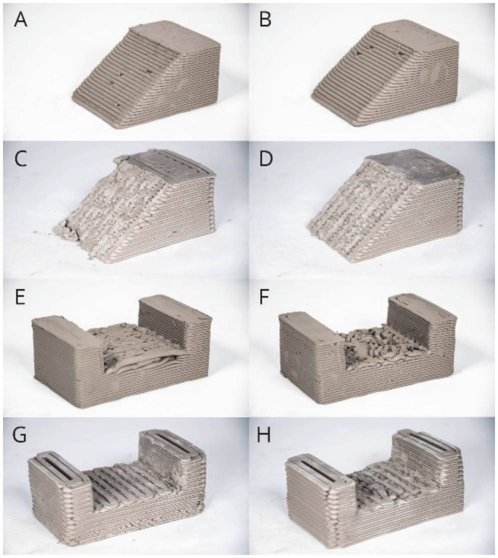


Figure 7
Overview of the results for printed clay supports
A: parallel 1,375mm
B: parallel 2,75mm
C: perpend. 2,5mm
D: perpend. 4mm
E: 1mm gap
F: no gap
G: comb-like 2,5mm
H: comb-like 4mm

Both specimens supported by a block (Fig.7 E+F) showed poor removability, as the bridging structure was firmly bonding to its support due to its own weight. This also resulted in a poor surface quality, as it was hard to determine at which point the support ended and the print began. Also, the gap in between the block and the print (Fig.7 E) caused immediate sagging of the strands and deteriorated geometric precision. Furthermore, this method required large amounts of material, which enhanced printing time. In terms of processability the alongside-printing can be described as favorable.

Thus, the removability of the comb-like structures (Fig. G+H) was not significantly increased compared to the first experiments, a somewhat higher surface-quality was achieved. Unfortunately the strands facing the prints surface firmly connected to it, so geometric precision was still negatively affected. Print-time decreased slightly, while the processability remained as favorable.

Support with interface-layers

Overhang. Beginning with sheet like-interfaces for overhangs, again a parallel and a perpendicular orientation of the supports were investigated. Also, plate-like interfaces have been examined, as they were expected to provide a better stability of their own than the sheets. Ultimately, fluid-like interfaces were tested, expecting an easy applicability within the process.

Both sheet-like interfaces, regardless if from foil or oven-paper (Fig.8 A+B), showed a good removability, regardless of the strand-orientation. In terms of surface-quality and geometric precision, parallel-oriented strands again proved as the better choice as the contact-surface was kept to a minimum. On the downside, processability is lower than just printing alongside, as first the support was printed, then the interface was placed and lastly the print itself was created. Depending on print-head-dimensions, print-paths, etc. the applicability of this method might be limited to simpler geometries. In comparison to supports only from clay print-time is not improved.

The Plate-like interfaces (Fig.8 C+D) showed good removability, while surface-quality and geometric precision were affected by the manual placement of the separation-plates (Fig.8 D). Also, the tendency of cardboard to absorb moisture led to distortions of the print (Fig.8 C), which was not observed for the foam-plate. Printing time turned out favorable, as the plates only needed few printed supports due to their own stability. In terms of processability, plate-like supports performed similar to sheet-like.

Only fluid-like interfaces performed very different from each other. While the sprayed oil (Fig.8 F) interface on parallel-printed support showed good removability, surface-quality and geometric precision, print time was high. Also, processability was comparable to sheet- and plate-like supports, being manufactured in three steps. The printed-cellulose-paste (Fig.8 E) on the other hand was not easy to remove, left an uneven surface with at least a good geometric precision. In terms of printing-time and processability this method was the most complicated, as it required a 3 step-process, which included changing the printer-fed material twice.

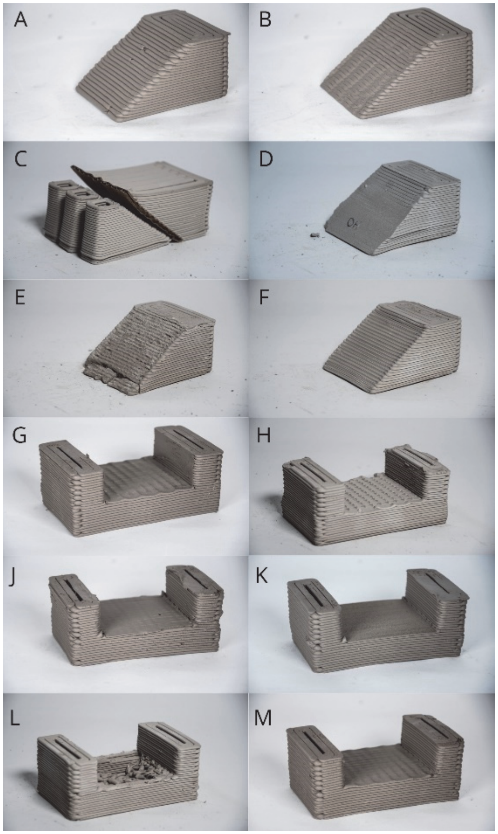


Figure 8
Overview of the results for interface-layers
A: foil
B: oven-paper
C: cardboard
D: foam
E: cellulose-paste
F: sprayed oil
G: foil
H: oven-paper
J: cardboard
K: foam
L: cellulose-paste
M: spraied oil

Bridging. Sheet-like interfaces for bridges, again both from foil and oven-paper (Fig.8 G+H), showed a favorable removability. Also, a good surface-quality, comparable with a usual print-bed as well as good geometric precision were achieved. While printing time remained the comparable to in the comb-like supports, processability was easy as the alongside print was just stopped at a certain height to place the sheet.

In terms of the plate-like interfaces (Fig.8 J+K), removability again was good, leaving favorable surface-qualities. Unfortunately geometric precision was negatively affected by the shrinking of the clay, which led to geometric constraints causing the prints to distort. While printing-time again could be reduced due to the plates own stability, processability was also good, as the alongside prints only had to be paused shortly to place the interfaces.

Fluid-like interfaces again behaved rather different from each other. The sprayed oil (Fig.8 M) caused a good removability and thus leaving marks from the direct contact of the strands the print showed a reasonable surface-quality and geometric precision. Printing-time was similar to printed supports without interfaces, while the processability only required a short pause in the alongside print to deploy the oil. Printed-cellulose (Fig.8 L) as an interface, in turn was hard to remove and even caused breakout of the supported bridge, leaving a bad surface-quality and low geometric precision. Also printing time was high and changing the printed material twice negatively affected processability.

Placed Support

Overhang. While showing good removability and surface-quality, placing a wedge-shaped support beneath the overhang (Fig.9 A+B) required a certain initial effort, as the pieces have to be prepared and set into the right position. Also, printing-paths had to be closely examined to avoid a collision of the nozzle and the print. In turn, print-time was noticeably shortened, which makes this method very suitable for small series, as the prefabricated supports can be reused. In terms of material, XPS-Foam (Fig.9B) proved as the better option, as cardboard again caused an unfavorable distortion (Fig.9 A) of the printed object resulting in low geometric precision.

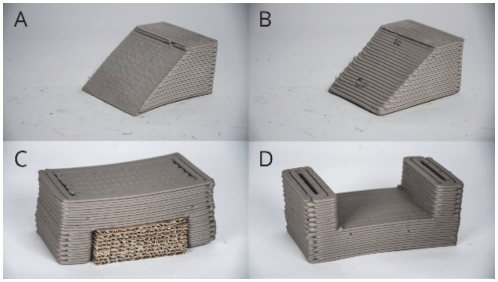


Figure 9
Overview of the results of placed supports
A: foil
B: oven-paper
C: cardboard
D: foam

Bridging. Placed supports for bridges (Fig.9 C+D) were easy to remove from the print and showed a good surface-quality, comparable with a print-bed. Again, due to the specimen's geometry and clay's shrinkage while drying, the placed caused the prints to distort, which negatively affected geometric precision. Even though this method assured shorter printing times and less usage of clay, it does not seem applicable for all kinds of geometries. Processability again was easy, as the print only had to stopped at a certain height to place the block.

Evaluation

The strategies were evaluated in terms of easy removability, surface-quality in comparison with unsupported prints, low printing-time, geometric precision compared with the digital model and a low-effort processability of the method as displayed in Tab.1 and Tab.2. As none of the investigated methods appear as ideal in every use-case, much depends on finding the right measure for the individual case.

APPLICATION ON GENERATIVE DESIGN

To apply the findings, the representative architectural geometry was printed once again. In this second stage, overhang was set to 52,5°, while bridging was set to 30mm.

In order to print the illustrative, a mix of several strategies was used. First, in the lower part of the void, a block of foam was placed to reduce processing time. For the support of the overhang, a parallel support with a distance of 50% of the strand-width was provided. To avoid complex printing paths, manual interventions and the long process-time resulting from this, it was renounced to place an interface-layer in between the sloped support and the print. Ultimately, for the bridging part at the top an interface-layer from oven-paper served as a separation between the support and the print. Placed supports were removed as soon as possible to avoid distortions caused by constraints.

Table 1
Evaluation of strategies for overhangs

Overhang	Removability	Surface-quality	Print-time	Geometric prec.	Processability
Printed, parallel	++	++	--	+	++
Printed, perpend	--	--	-	--	++
Interf. foil	++	++	-	+	-
Interf. ovenpaper	++	++	-	+	-
Interf. cardboard	++	+	+	-	-
Interf. foam	++	+	+	++	-
Interf. cellulose	-	-	--	+	--
Interf. oil	++	++	--	+	-
Placed cardboard	++	++	++	-	-
Placed foam	++	++	++	++	-

Table 2
Evaluation of strategies for bridges

Bridging	Removability	Surface-quality	Print-time	Geometric prec.	Processability
Printed, block-like	--	--	--	--	++
Printed, comb-like	-	-	-	-	++
Interf. foil	++	++	-	++	+
Interf. ovenpaper	++	++	-	++	+
Interf. cardboard	++	++	+	--	+
Interf. foam	++	++	+	--	+
Interf. cellulose	--	--	-	--	--
Interf. oil	++	+	--	+	+
Placed cardboard	++	++	++	--	+
Placed foam	++	++	++	--	+

Figure 10
Altered illustrative piece with 52,5° overhang and 30mm bridge

The printed pieces showed reasonable applicability of the strategies carried out, good removability of the support-structures and satisfactory surface-qualities as well as geometric precision. In comparison with the unsupported piece, the geometry was enabled to span 398mm wide, while it was limited to 217mm before.

Figure 11
Comparison of the illustrative pieces

CONCLUSION AND OUTLOOK

During the first tests it became clear that robocasted components show almost no ability to perform any bridging and therefore need support. On the other hand, overhanging-abilities very much depend on the nozzle-to-layer-height-ratio, at least enabling slightly inclined surfaces. Very steep overhangs in turn result in poor surface-quality with a visible stair-effect. The mixture used showed 37,5° to 52,5° as a suitable range for supported overhangs.

In the scope of this research it was not possible to identify the "perfect" strategy to support Robocasted building elements. Rather a set measures has been tested and evaluated (Tab.1+2), most are suitable for the task, but they all come with their own pros and contras. As shown in the creation of the second illustrative, a mixed set of multiple complementary measures can also be an appropriate way to achieve the desired result.

As an outlook, using a printed cellulose interface-layer appears promising for further investigations, as printing cellulose is a technology closely related to Robocasting. Even though in this research, cellulose did not perform well due to its firm adhesion to the printed object and the high effort required to carry out the process, it is likely that improvements can be made to overcome these disadvantages. To improve processability, the deployment of cellulose may be integrated directly into the process by using a dual-nozzle-setup. Also, altering the mixture of the cellulose-paste to make it less adhesive to the printed object may lead to better removability, which again may lead to improved surface-quality and geometric precision. Ultimately, a process-integration may enable the creation of complex geometries in an alongside-print of a print and its support.

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