Ruin prosthesis

Graduation research paper

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Abstract:

In this research paper, the implementation of 3d scanning combined with digital fabrication in the process, design and production of an architectural extension onto a monumental ruined structures is examined. First, a study to precedent ruin extensions has shown specific technical requirements and difficulties of building on ruins. Secondly the workings of 3d scanning have been studied in both literature and practical experiments in order to state their suitability for the proposed design. With the obtained knowledge, a few proposals for building details that integrate digital capture and fabrication with standard building methods are conveyed and studied to conclude that the method has great potential and should be elaborated further in prototyping on architectural scale.

Keywords: 3d scanning, digital fabrication, architectural engineering, prosthesis design

Introduction

From representation to production and craft

The present time is often deemed as the ‘digital age’. It indeed is safe to say that the computer has influenced our everyday live in many ways and had an impact as extensive as followed from the industrial revolution. The initial effect of this digital revolution on architecture was limited and mainly contained the design communication. Slowly but surely, a drawing became a file, the cardboard model became a 3d computer model but the building practice itself was not fundamentally changed. Were digital used to be only present in the area of representation, in the last decades digital has become a term also applicable to production and craft.

Customization of design

Inclusion of digital techniques in production can amount to fundamental changes in design. Design can be more specific, more detailed and less repetitive because the production of unique elements has become as efficient as the production of identical ones in the process of digital fabrication. This customization of design is especially relevant in architecture. Here specific site conditions, culture, personal preferences etc. make each project unique. The challenge that is in front of today’s progressive designers is to find out how and where to implement this customization. The use of digital fabrication does not only allow highly specific solutions. It demands it.

Physical to Digital to physical

The computer as a tool for design has made new forms in architecture possible. Buildings designed and manufactured completely by the computer have been claimed to produce architecture that is unspecific and not related to its place and context. There is a strong relation from the digital towards the physical world, but the physical world (site, morphology, culture) is not often used as input in digital design. The translation from digital to physical is still only a one way crossing. Digital data can be put into the physical form, but the reverse – the translation of the physical

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world to digital input in design - is hardly a factor in the design and building of architecture. Recent developments in 3d scanning technique make it possible to generate that specific input. This can form a two way crossing between the digital and the physical world. With the incorporation of reality capture in both design AND production, it is my vision that digital techniques can bridge this gap between computational design and its physical context. As Bob Sheil states: the focal point for advanced technologies in architectural design has shifted from the virtual to a hybridity with the actual.3

Changing role of the architect
The use of the described workflow from digital capture to fabrication implies a change in the role of the architect within the process of building. Conventionally the architect delivers drawings to the contractor and the builders. When building(parts) are digitally fabricated, the architects drawings can be directly translated to building elements and the extra translation of the contractor becomes redundant. This will require more practical knowledge from the designer, but also offers the opportunity to be more involved in the building process and be more precise in the execution of the design. A architect can become a master builder again.4

High definition
Both 3d scanning and digital fabrication offer a very high definition of form. ‘Such a potential for complete control is both liberating and paralyzing – freeform high-definition fabrication requires an equally high-definition design context’.5 To successfully demonstrate the full potential of the incorporation of reality capture in design we are in need of a very complex context to design with. The hypothesis that started this research is that the perfect context and breeding ground for the proposed technique are monumental ruins. Being both delicate, complex and highly irregular in form, ruins pose a challenge to design with.

Building on ruins:
To design an architectural extensions on to a ruins is a very charged assignment. The designer has to take a firm position and define what the role of the extension in the ensemble will be. A beneficial use for an old building makes it far more likely for the building to survive, but existing structures are often difficult to adapt to its new function. The need for a practical use and the inability to damage or change the structure - either in form and in character - illustrates the field of tension the designer enters. He will have to mediate between pragmatism and romanticism. A series of case studies on ruin extensions shows that technique is often the key aspect to a successful articulation of this position. Two of those cases have been studied in greater dept and will be discussed later on. The position that the architect takes to the design is the most tangible at the join of old and new (fig 2). The use of digital capture and fabrication could be the tool to make that join in a more specific, more customized and more elegant way than before.

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3 Sheil, B. (2014)  
4 Stoutjesdijk, P. (2013)  
6 M. Davies (2011). New life for old ruins, from Buildingconservation.com
Research objective: Tool for design
The objective of this research is to investigate how this new tool would work and where it could be implemented. The classification of the technique as a tool does not mean its importance is little. It were simple tools like flint stones, the wheel and the steam engine that have led to revolutionary progress in history.

In the words of Chris Andersen: ‘really powerful changes come from new tools. And there is no tool more powerful than the computer itself’7. At the same time it is important that tools don’t become dogmatic in design. The tool remains a means to a goal, not a goal in itself.

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Research Methods

This research is structured to answer the following question: how can digital capture and digital fabrication be used to build a ‘prosthetic’ connection to a monumental ruined structure? The research will be structured in the different steps that follow from the proposed method. Each of those steps summons questions that need answering and ask for its own method of research. The research is divided into three chapters that each deal with a phase of that workflow. The next page shows a scheme of the described research structure.

The first section of this paper consists of an investigation of the technical requirements and limitations that are consequence of building onto a ruined structure. Construction onto a ruin is rare but not unprecedented and some information is obtainable in the experience of those who have built them and by studying completed projects. Research methods will be case studies of two architecture projects - chosen from multiple projects because of their interesting technical solution, architectural appearance and the availability of information. Secondly interviews conducted with two experts in renovation architecture and Serge Schoemaker, project architect of Kolumba Museum should provide more insight in general difficulties and the building process.

The second section deals with the transfers from physical form to a digital model and its translation into production. The digital capture phase is the most emphasized in the research since it is the most innovative part of the proposed design method. 3D scanning is widely described in literature, but the application of this technique as direct information for production in architecture is very rare and that information is limited. Therefore the first methods of research will be a literature study to gain insight in the technique of 3d scanning. Later in this chapter we research the suitability of digital capture techniques for design and production purposes. This is done researched by design; In 4 small scale design experiments that extend from capture, to production of a prosthesis.

The third chapter is a brief investigation of how the proposed techniques and knowledge can be integrated with existing building methods for architecture. And how this will make them suitable as building methods for extension design. Research methods are literature research and research by design. This last chapter should be a test of the practical utility of the obtained information and the opportunities that digital capture provides. This will be further reflected upon in the conclusion.
How can digital capture and digital fabrication be used to build a ‘prosthetic’ extension to a monumental ruined structure?

ruined structures
- What is the load-bearing capacity of a ruin?
- How does the architectural position inform the technical design?
- Which building methods are applied to extend a ruin?

Research methods: case studies, interviews

digital capture & digital fabrication
- What scanning techniques are available?
- How do they work?
- Which ones could be applied to a ruin?
- How accurate, quick, expensive etc. are they?

Research methods: Literature, experiments

prosthesis design
- What building methods could be compatible?
- What might a connection look like?
- How are they produced?
- How to assemble the elements?

Research methods: Literature, research by design

Conclusions

further research
1. Conditions of ruin renovation

This chapter of the research consist of an investigation of the technical requirements and limitations that are consequence of building onto a ruin. Insight in ruin By performing case studies to two projects; The Kolumba Art Museum, designed by the office of Peter Zumthor and The East Wing of the Naturkunde Museum in Berlin by the office of Diener & Diener. The aimed result of the research is to have gathered insight on what demands can be set for architectural extension of the ruin in aspects of structure, climate separation and aesthetics.

The Naturkundemuseum in Berlin
The Museum of Physics in Berlin is a vast complex designed by August Tiede in 1889. The east wing of the museum was destroyed by a bomb during world war II. The entire roof structure collapsed into the basement and parts of the façade where lost (fig. 1). The renovation designed by Diener and Diener architects from Switzerland was inspired by Paul Klee’s restoration of the painting Die Tierschicksale (fig. 3). Klee reconstructed the parts of the painting that were damaged by fire, by repainting the missing in a monochrome brown. The monochrome addition modestly reinstates the original composition of the painting but is at the same time clearly differentiable from the original painted parts. The renovation of the east wing consists of a reconstruction of the original façade made in prefab concrete elements. The renovated east wing serves as archives for the 170,000 specimen in ethanol. These specimen are put in a freestanding glass box in the middle of the 300m² room and desire no daylight and a constant relatively cool temperature. This enabled the reconstruction of the façade to work with completely closed facade elements and to brick up the still remaining window frames of the east wing.

Fig. 3  The East wing in the ruined state, from www.competition online .com (6-5-2015)
Fig. 4. Tierschicksale (1913) painting by Franz Marc. The brown parts on the right of the painting are reconstructed. Image from www.crarch-design.ch (6-5-2015)
Façade of precast concrete
The façade elements are produced by making a mold based on a silicon print of the original repetitive façade fragment. Inside these concrete panels are the actual structural concrete walls with insulation. The design can be read as a complete new building erected within ruined walls of the east wing with concrete panels as cladding that is fitted precisely to the existing remains. By reading the pictures and the drawings you can tell that the ruin had to be modified to be able to accommodate the straight lines of the concrete panels. Bricks have been entirely or partially removed and flattened until there were straight line for the panel to fit in. The removal of the top layer of a ruins bricks can also be because out of the bricks of the wall, these stones will be most damaged by weather influences. It is likely that production was done in the following way: two molds are made of the respective façade elements (a different one for the top floors). Only five of the 11 placed panels could be made directly from these molds. To make the other six panels the molds had to be manually adapted with filling to exclude the parts of the existing ruined wall in the new panel (see img. 5 & 7). It can be concluded that even though the building looks like a healing of the former façade. She is in fact a new structure inside with a precisely fitting outer skin. To make this precise fitting of the outer skin a smart technique of silicon prints and a lot of hand work was performed to adapt and measure both the ruin and the new façade elements.

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8 Interview with ir. Frank Koopman, construction specialist of heritage buildings and renovation, conducted 08-05-2015
**Kolumba Kunstmuseum, Cologne**

The Kolumba Art Museum was built upon the ruins of the former gothic church of saint Kolumba that hit by a bomb in the second world war. The design competition commissioned by the bishop of Cologne was won by Peter Zumthors office who created an interior space formed by extending the walls of the old ruins with partially perforated brickwork. The enclosed space contains an archeological site with roman and medieval findings and a 1960 chapel built in honor of the Maria sculpture that miraculously survived the bombings. The aim of the renovation/extension was to build a harmonious whole with the ruin. Zumthor proudly proclaimed they did not have to remove a single stone from the ruin. Serge Schoemaker - project architect overseeing the execution - explains the construction as a technical challenge. For one, the construction engineer did not want to take risks by putting a load on the collapsed walls of the old church. Although it is plausible that those walls could still carry quite a load since they once held up an entire church. It is however hard to test the loadbearing capacity and unsafe to take such a quality for granted. Therefore the old walls only carry the first floors layer of brick. To support the museum, giant diamond drills were used to drill trough the ruin to the foundation. The building is in the end supported by the metal columns that run through the ruin to the original foundation.

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10 Interview with Serge Schoemaker, 08-05-2015
Regarding the constructing, the building can be described as a building lifted above a ruin. The new part of the building is made of a custom white brick produced in Denmark. It proved very difficult to make a sound connection of the new building to the ruin. One of the main issues was that none of the church walls was straight in horizontal or vertical measurement. To connect to the construction above all ruin walls had to be measured exactly and drawn out by an external company. The Kolumba museum is built by exact measurement and craftwork. The reason it is so highly regarded is that the building is harmonizes with the ruin and forges it into a new whole. The amount of care, precision and craft in the project are key in obtaining this quality.

**Control of irregularity**

In both cases of ruin renovation we see that the designers overcame a struggle with the complexity of the ruin by smart technique and labour. Existing walls often are not trusted with a structural function and masonry has poor insulation value. Zumthor and Diener & Diener have resolved this issue by building new respectively above and inside the ruin. The ruin walls function as a raincoat but the image of a single mass is achieved. It must be noted that there are examples of cases where ruins do have a load bearing function. By building with a similar material (stone) they avoid problems of material expansion. When building an extension of a different materials, the difference in material properties, most importantly their expansion rate under influence of heat, can cause problems with tolerances and put pressure on joints. This has to be taken in account in the design of the connection. Potential of digital techniques become clear upon studying these two construction processes on ruins. 3d scanning provides the exact capture of the ruin. This could be useful for to create a drawing to work from but could also be directly translated into the fabric of prosthesis. This might have been a neater and quicker way to produce the molds for the Naturkunde museum, for instance, leaving more of the ruined wall intact.

Fig. 10 Wall of Saint Kolumba church, image from Diener & Diener architeckten, (2013). Neubau des Ostflugels [Press]

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11 See for instance Astley Castle, UK

12 Interview with ir. Frank Koopman, 08-05-2015
2. Reality capture techniques

There is a wide variety of techniques available to translate the physical world into digital models (digital capture). This chapter of the research is purposed to select which of those methods and devices are applicable for the proposed design of an architectural ‘prosthesis’. With a few of the selected capturing techniques, scaled experiments with ruined objects and structures will be performed in order to investigate the performance of these devices in the proposed workflow of digital fabrication from digital scan data.

From the wide range of capturing techniques, many are not suitable for use in design and construction. To be able to 3 dimensionally map a structure the capturing device has to be portable, and very accurate. In addition, the cost and working speed could be a factor in the selection of the technique and device for 3d scanning. The absolute need for portability rules out most of the available techniques among which all contact based scanning, scanners using a mechanical arm, and other stationary techniques like CT scanning. This study of scanning techniques will be limited to three specific techniques. These techniques are using either a laser or cameras and in most cases both at the same time. Laser scanning is already being used in building practice as a surveillance tool and photogrammetry is a very recent innovation that is easily accessible and can be tested to its accuracy.

**Photogrammetry**

In photogrammetry, a 3d model is created by making multiple images with a single camera. A server than stitches those images together by identifying similar pixels. It is this stitching process that makes it difficult to scan large even surfaces and prescribes the amount of photographs you need (usually around 40 for a small object). Taking photos from up close results in a very high accuracy but will be more time consuming. Reflective or transparent materials will not scan well because they cannot be stitched. Another precondition is that images are sharp and have sufficient exposure to light. The stitching and processing into a 3d file is often done by a central server with more processor power. This can take up to a day, depending on server availability, photo count and desired quality. The output is a detailed polygon model obtained in several standard 3d model file extensions. The 3d model has no orientation or absolute scale, this has to be done manually by performing reference measurement.

![fig. 11, Software calculates were pictures are taken from and stitches them together to a model.](image-url)
Laser triangulation scanning:
Laser triangulation projects a laser light onto an object. It has two infrared camera’s that capture the reflected light from the object and measure at what angle it reflects. It combines this information with the known angles of the infrared cameras and the distance between them to form a triangle in which it can calculate where the distance to the point where the laser hit the object. Repeating this process will result in a point cloud that forms the 3d model. There is a third camera (in the centre) that makes colored images of the scanned surface and adds a reflected color to the points in the point cloud. For (re)production purposes this is irrelevant but it makes navigation through the model easier. The resulting point cloud file has absolute measurements but needs an orientation. To be able to translate the model to fabrication it is necessary to transfer the model into a watertight mesh model. Several software solutions are dedicated to this, but it will cost time and effort. Scanners have problems with scanning of transparent or very reflective surfaces, also bright sunlight might distort the infrared light and therefore reduce the scan quality significantly. Scan test with two different laser triangulation devices has been performed and will be discussed further down.

Time of flight scanning:
Time of flight scanning is a technique that makes a 3d model by sending out a laser light in a precisely coordinated direction. The scanner has a sensor that captures the reflected beam and uses the known speed of light to calculate the exact distance from the scanner to
The model output is a point cloud of hundred thousands of points in a density of and a accuracy of about 2mm disregarded the scan distance (till over 100 meter). Orientation of the model is automatic because of the tripod it stands on. The scanning process is very fast. A room can be scanned in 15 minutes. The devices has to be set up, leveled and by the push of a button a scan starts. The effort towards fabrication is once more in the handling of the scan data. Software is used for the ‘stitching’ of several scans into a single point cloud model. By clicking parallel surfaces and by identifying one or more common points in two separate point cloud models, the two are stitched together.

Scan of an entire building might need the stitching together of 20 scans. The models often need manual solving of deformations (‘noise’) and the heavy point cloud models need a lot of adaptation towards a mesh model that is suitable for production purposes. Furthermore the accuracy might not be sufficient for the proposed ‘prosthesis architecture’. What would make this scan method very favorable over others is the quick scan procedure and the ability to capture many surfaces in one model, thus preventing effort and errors that come with stitching the models together. A setup would be possible were the scanner is on a lifted platform and scans all the lower walls of the ruin at once.

<table>
<thead>
<tr>
<th>Method of 3d scanning</th>
<th>accuracy</th>
<th>range</th>
<th>error probability</th>
<th>portable</th>
<th>speed</th>
<th>model output</th>
<th>cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>photogrammetry</td>
<td>0.3 mm</td>
<td>close up (0.1-1m)</td>
<td>medium</td>
<td>yes</td>
<td>low</td>
<td>triangulated mesh</td>
<td>none</td>
</tr>
<tr>
<td>laser triangulation</td>
<td>1.5 mm (differs per scanner)</td>
<td>&lt; 1m (0.5-3m (Faro freestyle)</td>
<td>Medium and long range (2m – 1000m, Faro Focus)</td>
<td>low</td>
<td>yes</td>
<td>high</td>
<td>point cloud</td>
</tr>
<tr>
<td>time of flight laser</td>
<td>2 mm</td>
<td>yes but limited</td>
<td>higher</td>
<td>point cloud</td>
<td>higher</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1, of Characteristics of scan techniques and table 2, of relative performance of tested devices, own illustration
2.1 design experiments;

Several experiments conducted to test both the scan quality and the practical utility of 3d scanning in the process of design and production onto highly complex and irregular surfaces. The tested scan technique include 2 photogrammetry solutions (123D catch, Recap), a high end laser triangulation scanner (Faro Freestyle), and a low budget laser scanner (Sense 3d). Regrettably, a time of flight scanner was not available for testing at the time. Reflection on the results of the scans, the transferability to a suitable model towards production, and the resulting product should provide deeper insight in the feasibility of the digital to physical process as a design tool. Furthermore it should uncover the difficulties and constraints that come with the process.

Design experiment: coffee cup prosthesis 1

This test case is a literal execution of the earlier presented diagram. The objective of the design experiment is to produce a prosthesis for a broken coffee cup that exactly fits the ragged edge were the shard broke off. This experiment consists of four steps which are the basic steps in the proposed design and production process:

1. The physical form of the cup is transferred to a digital model with the use of photogrammetry.
2. The form of the prosthesis is designed and modelled in 3d software and exported in the suitable scale and extension for production.
3. The prosthesis is digitally fabricated

1: 3d scanning of the object

To transfer the broken cup to a digital model photogrammetric software of recap 360 was used\(^\text{13}\). Images need to be well and evenly lit and the entire object should be in focus for proper scan results\(^\text{14}\). Artificial lighting was used from all sides. The cup was placed on a rotating disk and by using a tripod, and a large F-stop value on the camera it was ensured that focus was correct. Pictures were taken from a straight angle, rotating the disk a prescribed 5 degrees per shot. There is no software based solution to check the photographs on lighting and focus, so this has to be done manually. 50 pictures were uploaded to the Autodesk recap server of which only 34 could be stitched. The server needed 8 hours to process the images and calculate the form of a mesh model with over 320,000 triangles.

The model quality seems poor at first sight; at certain surfaces there is geometry bulging out of the cup, other parts are quite exactly captured. The reason for the deformations is most probably due to the reflectiveness of the material, this hypothesis is strengthened by the fact that the faults are mainly in the inner surface of the cup that is made in a more reflective glazing. The unreflective ragged edge of the broken cup is captured remarkably well and therefore the model is still suitable for production of the aimed prosthesis.

\(^{13}\) Free software available at autodesk.com
2. Designing and Modelling the Prosthesis

The polygon mesh model is imported into 3D software. This has to be an advanced 3D modelling software to be able to handle the complex model. Autodesk Maya\textsuperscript{15} was the software used to model the missing piece of the rim of the cup, using the 3D scan as a base to draw from. To make the form fit the edge the Boolean function was used that ‘subtracts’ one form from the other. The resulting 3D model had the desired form of the prosthesis to be fabricated.

3. Digital Fabrication of the Prosthesis

The fabrication of the cup prosthesis was done by a 3D printer. The printing needs little preparation. After loading the model to the printer it took an Ultimaker 3D printer about 40 minutes to print the prosthesis, with material density of 30%.

Coffee Cup Prosthesis 2

A Second attempt at the coffee cup prosthesis was conducted with the Faro Freestyle 3D scanner. A high end model laser scanner based on triangulation used in building surveillance and BIM modeling. Due to the angles of the camera’s the scanner has a focus distance of a minimum of 50cm. At this distance it will scan much more than only the coffee cup. The point density and accuracy on the coffee cup are problematically low when we convert the point cloud to a triangulated mesh, there are too few points to get a viable result (fig. 17). The form of the cup seems inaccurate and the entire rim of the cup disappears. No prosthesis could be produced from this scan.

Coffee Cup Prosthesis 3

A third go at the coffee cup prosthesis is performed with the Sense 3D scanner. Just like the Faro Freestyle, this is a 3D scanner using infrared light and camera’s to perform triangulation. It is however a low budget model aimed at and affordable for consumers. The scan software is quite simple, the only important device setting being the object size. Scanning with this device proved quite difficult. Any shaky movements resulted in poor scanning quality. Therefore a tripod and rotating disk were used. This would complicate scanning anything in situ. The resulting scan does have a high definition of 200,000 triangles but the numerous errors make the scan quality poor. The scan is the right scale but with the naked eye one can see that there is geometry bulging out everywhere and many angles are crooked. A 3D print in gypsum shows that the scan took the overall form but has a lot of errors and does not fit exactly (fig. 18).

\textsuperscript{15} Other high end software solutions are Rhino or 3D Max

Fig. 17. Coffee cup prosthesis 2.0. Screenshot from the point cloud model and resulting mesh own image
Fig. 18. Coffee cup prosthesis 1 & 3.
Above: Screenshot of resulting model from photogrammetry.
Left below: Cup prosthesis from that model.
Right below: Cup prosthesis result from the sense scanner.
Own images.
Design experiment: Prosthetic shelf
The objective of this last design was to make an esthetically pleasing bookshelf that is supported by an exact fit into the two heavily damaged brick walls that side a window frame. This is a context because it has the same scale and material as the ruined structures that we are trying to build on. Window frames in particular pose problems to adapt to because of their culminating irregularity.16

The scan technique that was used was photogrammetry since it had produced satisfying but irregular results on the former experiment. For this design experiment the phone application 123D catch was used.17 The application provided help in positioning towards the desired object to capture and eased the workflow of taking, reviewing and subsequently uploading pictures to obtain a model, compared to other photogrammetry solutions. The models of the two sides of the wall that were captured this way were indeed very accurate at sight. The biggest challenge in working towards a physical fabrication was not the scanning, but the scaling, orienting and leveling of the resulting models. This could have been made easier by two changes in the setup;

- capturing the two window sails in one single scan.
- placing a specially designed object with a known length and in the scan area that helps with scaling and orientation.

The design was to make two consoles that would rest the shelf. If the entire form was prefabricated it would not be possible anymore to put the shelf in its place. The envisioned method of digital fabrication- CNC milling- meant that the form had to be subtractable from above with a maximum depth of around 6 cm. Therefore it was chosen to make the consoles as abstract blocks. The milling is time consuming due to the fine detail aimed to achieve. It took the ISEL flatcom CNC milling machine 14 hours (unsupervised) to mill the two consoles. Together those consoles only fill 300 square centimeters of wall surface. This is mainly due to the large amount of detail. By finding an optimum in the required amount of detail and using a rougher mill, the fabrication time can be reduced drastically. Some time-reduction will be necessary to make the technique feasible on the scale of a ruin. Of the resulting consoles, one slotted into the wall easily with a near perfect fit while the other console needed some minor adjustments. Possible problems at this right console proved that either an error was made with the manual scaling by reference measurement, or the photogrammetry had flaws due to insufficient focus or lighting. Wood turned out to be a good choice of material cause it is easily reworkable; with ten minutes of machine sanding the console fitted. The consoles and the shelf were formed and cut to measure by hand. It used more traditional techniques, and slot and pin-hole connections. The product is firmly fixed and loadable but did not need to damage the building in any way. The result shows the potential for fitting by form. It has structural advantages and provides a completely reversible intervention that complies with heritage demands and is architecturally interesting.

Fig. 19. Prosthetic shelf, own image
3 Integration of digital capture and fabrication in standard building methods

To apply the demonstrated method of digital capture to production on an architectural scale, it needs to be integrated with standard methods and materials of building. This is explored in the making of two sketch designs. To be able to assess the possibility of integration it was necessary to gain some from knowledge from literature about the production process. The possible solutions should be completely reversible and should not damage the ruin structure.

1: The creation of a window frame in difficult areas of the ruin wall

For the design of the window frame, the material wood is chosen because of its appearance and good formability, as demonstrated with the prosthetic shelf. The design proposal is to use the CNC mill and scan data to make a frame that fits the ruin exactly. As seen with the prosthetic shelf, the window can’t be prefabricated in its entirety because then it will not fit. It has to be made in separate pieces and fixed in situ. In fig. 20 you can see how a window frame has to be made up out of several parts to be able to slide them into the wall corners. This montage of parts is not a problem per se, standard window frames, which are also made up out of multiple parts laminated and glued together. It must be noted that this customized method of assembly in place will require extra attention and is probably more difficult.

Right: Fig. 20. Top: Sketch of CNC milled window frame and assembly order, own ill.  
The window frame should not connect with the brick wall unprotected. Brick absorbs and releases moisture that can damage the frame if it transfers materials too easily. Further problems might occur because of the different expansion coefficients of the brick and wood and cracks might appear\(^\text{18}\). The detail drawing therefore shows a thin layer of neoprene that should seal the wood from moisture and leave some ‘breathing space’ for the expanding construction. This connection should be tested and become much more elaborated.

2: loadbearing walls in custom prefabricated concrete panels.

A second challenge is to find a technical solution for building a structural connection to the ruin walls. This connection should preferably be load bearing (provided that the ruin is able to found this). Inspired by the example of the Naturkundemuseum Berlin, prefabricated concrete elements were chosen. Advantage of these elements is that they can have load bearing capacity and integrated insulation. Also the method of casting in molds makes the free form possible. It will take an adaptation of the standard process of concrete casting to create made-to-fit elements. Smart solutions for adapting the mold casting process were shown by the flexible mold method that created a mold that is adjustable to many curved shapes while the concrete is hardening and is reusable\(^\text{19}\). Another example is the development of 3d printed molds to create free form columns by concrete firm Bruil\(^\text{20}\). This technique of mold printing is beyond initial prototyping and is currently being tested in full scale building projects.

Prefabricated wall elements are normally cast in three phases on a flat table mold. Firstly the mold is sprayed with a separation agent. The bottom of the molds can contain special sheets to make embossments on the surface. A wire mesh is placed in the mold and cast in a layer of concrete. In the second phase insulation is applied with connectors to the concrete slabs. finally the last layer is cast in pre-stressed steel rods and a wire mesh. The panels are connected into a single structural slab either by metal connections that were inserted in the mold, or by casting together panels with seam in situ.

The design proposal suggests a mold that is adjustable to different sections of the ruin wall. A 3d printed inlayed form (Bruil technique) adjusts the mold to different wall parts. The mold is reusable with different filling pieces. A challenge of designing this production method will be to make the adjustable inlays completely compatible with the rest of the system. For instance: how will the structural reinforcement run through the free formed inlays?

\(^{18}\) Interview Frank Koopman

\(^{19}\) Schipper, H., & Janssen, B. (2011). Curving Concrete, TUdelft

\(^{20}\) http://3dprintmagazine.eu/slimme-toepassing-3d-printen-voor-betonconstructies/
Bottom:
Left: stills from the video ‘Pre-Cast Concrete Walls | How It’s Made’, broadcast by Science channel, available at https://www.youtube.com/watch?v=HO7EcUtswcl
Right: image adapted from Edward Losch’ lecture ‘precast wall panel design’.

Images: Top
Left: wall section, own illustration
Right: Adaptable mold for prosthetic panel production, own ill.
Conclusion & Discussion

In the introduction it was stated that digital fabrication technologies demand highly specific problems, in order to deliver customized solutions and reach their full potential. From case studies it can be concluded that designing on a ruin is such highly specific problem. When the designer positions himself in favor of retaining he will have to struggle with great complexity and irregularity. The studied projects showed different solutions to deal with this complex irregularity. The office of Diener and Diener invented a smart technique that was incorporated in standard concrete pre-casting. Peter Zumthors office made an elegant connection by deploying an endless amount of craft. A further important observation is that while both designs put effort in restoring the ruin they do not restore the structural or climatologic functionality of the wall. Further study to the possibility of building on a ruin structurally. This ruins should be studied case specific because of the great differences in decay and damage.

Reality capture offers several techniques that could be applicable to use for direct translation of 3d scan data to production. Photogrammetry, laser triangulation scanning and time of flight scanning by laser are the three techniques that have been researched. There is a big difference in price that does not necessarily align with the performance. From testing the devices it appeared that none of the devices were made to perform as a translator to physical production in real life scale. Devices were either for commercial entertainment or for surveillance purposes, making models to take measurements. Problems that sporadically occurred were too low resolution, difficult data transfer, scan errors, and complicated model handling. In spite of these occasional flaws, it was possible to make a suitable model for a prosthetic connection. Remarkably, the cost-free photogrammetry applications were best suited to the purpose out of the tested devices to make a prosthetic connection. This was mainly because they offered the highest resolution. In the software’s current state, it would be time costing and impractical to use on a structure of architectural scale. The best solution would be a laser triangulation scanner with a much closer focus point and a mesh model output. Further research can be done to find the perfect scanner but from this research it can cautiously be concluded that the technology is advanced enough to accommodate the proposed design method. Tests with a time of flight scanner for its ability to make a prosthetic connection could not been performed yet in this research. The results of those tests will be added to this report opportunely.
The experiment of the prosthetic shelf shows the potential for an exact connection to the highly irregular form of a ruined wall. The form-fit offers a stable and structural connection and provides a completely reversible intervention with an esthetically pleasing seam, as can be seen at the image at pg. 2. On the other hand the aim of this research was not for interior elements. The execution took much effort and time. In order convert this potential into a suitable building method, a smart process of capture and production should be developed that makes it possible to make bigger elements more efficiently.

Chapter 3 of this research was just a beginning in conceiving these methods that integrates digital capture and production tools with more standard building methods. This solution seemed plausible but those research designs are still preliminary and hard to value. In order to evaluate them proto-types should be made. In this brief research just two materials and processes have been examined and combined. More materials and combinations could also be researched and developed into prototypes. What can be drawn from this research is that the technique has enough potential and some positive signs of the technical support to engage optimistically in such prototyping.
Literature


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