The Tectonic Potentials of Concrete

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THE TECTONIC POTENTIALS OF CONCRETE

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The Tectonic Potentials of Concrete

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DANSK RESUMÈ

Nutidige teknikker til betonstøbning i arkitektonisk sammenhæng er udfordrede af krav om øget individualisering i det byggede miljø såvel som minimering af ressourceforbrug og udledning af affaldsstoffer.

I de senere år er der sket en udbredelse af nye produktionsteknologier og –strategier, der bryder med det industrielle paradigme om mest mulig standardisering. Denne udvikling bæres frem af computere og digital fabrikation, men er fraværende i produktionen af bygningskomponenter. Eksisterende forskning indenfor betonstøbning har dog medført en udvikling mod øget individualisering af støbeformene. Hypotesen i dette projekt er, at de anvendte teknikker ikke til fulde adresserer betons tektoniske potentialer, hvilket afstedkommer følgende forskningsspørgsmål:

Er det muligt at forbedre eksisterende eller udvikle nye betonstøbningsteknikker, som tillader individualisering og ressourceoptimering og samtidig matcher eller forbedrer de tektoniske potentialer som findes i eksisterende, repetitive betonstøbningstekikker?

Forskningsprojektet består af to tilgange til feltet: Et *empirisk studie* af nutidige støbeteknikker og efterfølgende seks *case-studier*, udført som *research by design*. Det empiriske studie er foretaget for at finde tektoniske implikationer og udfordringer i eksisterende støbeteknikker. Disse implikationer danner udgangspunkt for formuleringen af case-studierne, som har til formål at vurdere tektoniske potentialer i eksisterende støbeteknikker og udvikle nye. Det er gennem analyse af de empiriske studier og de eksperimenterende case studier op mod et teoretisk begrebsapparat, at konklusionerne drages og svar på forskningsspørgsmålene foreslås.

Et sådant begrebsapparat udfoldes på baggrund af toneangivende udgivel-

ser vedrørende tektonisk tænkning. Den tyske arkitekturteoretiker Gottfried Sempers ideer bliver præsenteret som en strategi, der kan beskrive geometrisk form som et resultat af materielle og tekniske omstændigheder. Derudover præsenteres ideen om den poetiske konstruktion af den engelsk/amerikanske arkitekturteoretiker Kenneth Frampton. Ideen er at den poetiske konstruktion kan opnås, hvis opmærksomheden rettes mod *materialernes egenskaber*, *deres strukturelle logikker* og *deres frembringelse*. Marco Frascaris tanker, som fremhæver *detaljen* som betydningsdannende element introduceres som en måde at skabe progression i case-studierne. På grund af fokus på skabelsen af beton introduceres endnu et begrebsapparat, der fremhæver tektonik som fysisk fænomen: Forholdet mellem materiale, teknik og form. Endelig sondres der mellem forhold omkring skabelsen af støbeforme og skabelsen af den egentlige betonkonstruktion. Det første benævnes *støbeformstektonik*, det sidste *betontektonik*.

Et studie af koncepterne 'Ny Produktions Filosofi', 'Mass-customization' og 'Digital Tektonik' præsenteres som baggrund for at undersøge deres relevans for betonstøbning. Digital modellering og simulering som gengivelsesstrategi præsenteres som en metode til at vurdere både geometri og fremstillingsprocesser samtidig.

For bedre at forstå potentialer og problemer i de undersøgte teknikker foreslås en skelnen mellem addition, subtraktion og transformation (A-S-T).

Addition konkluderes at være det at mest udbredte princip i nutidig praksis, hvor sammenstillingen af euklide formelementer udgør rektangulære støbeforme som udgør en geometrisk restriktion i forhold til betons iboende isotropi.

Subtraktion derimod, konkluderes at være den mest udbredte teknik til at støbe komplekse betonelementer, hvor ressourcer spiller on rolle, men alle nuværende subtraktive teknikker medfører en overflade af lav kvalitet.

Transformation udvikles gennem støbning i tekstil. Det konkluderes at teknikken medfører manglende præcision, hvilket udgør et problem, når flere betonelementer sammensættes og i situationer, hvor elementer møder rektangulære og præcise bygningskomponenter såsom vinduer og døre. Dette adresseres gennem udviklingen af en ny støbeteknik hvor laserskæring og foldning af store ark PETG plastik anvendes, hvorved præcisionen bevares. Muligheden for at genbruge PETG formene gør, at denne teknik er uden spild.

Generelt konkluderes det, at problemerne i de eksisterende støbeteknikker relaterer sig til produktionstid, overfladekvalitet, og præcision og skyldes anvendelsen af fremstillingsteknikker og materialer relateret til udfærdigelsen af støbeformen. Disse problemer med *tektoniske relationer i støbeformen* adresseres i case-studierne. Med udgangspunkt i disse konkluderes det, at logikker omkring *teknikken* bør være en bestemmende faktor for formgenereringen snarere end et middel til at opnå en forudbestemt geometrisk form. Dette medfører reduceret fabrikationstid og tættere tektoniske relationer i og med at teknikken kommer til *udtryk* i den geometriske form. Forskellige designforslag udfærdiges for at underbygge denne påstand.

På baggrund af problemet med dårlig overfladekvalitet i eksisterende teknikker, der anvender ekspanderet polystyren (EPS) som forskallingsmateriale, konkluderes det at *støbning* af EPS under tryk mod en indstillelig membran i stedet for *skæring* af EPS tillader frembringelsen af amorfe betonelementer med en høj overfladekvalitet. Samtidig forkorter denne teknik produktionstiden markant i forhold til eksisterende teknikker.

Det succesfulde design og konstruktionen af en forskningspavillion med brug af den foldet PETG plastik teknik anskueliggør, at computerdrevet parametrisk og algoritmisk design understøtter frembringelsen af betonstrukturer der responderer på mangeartede formationelle, materielle og kontekstuelle forhold. Dette er dog under forudsætning af, at disse generative teknikker anvendes i en iterativ proces med fokus på at udforske grænser snarere end at definere løsningsrum. Det objektorienterede designparadigme konkluderes at understøtte en sådan udforskning idet programmeringskode kan opdeles i 'klasser' såsom koncept, geometri/materiale og fabrikation.

Baseret på en analyse at de empiriske studier og case-studierne udpeges fire essentielle egenskaber vedrørende støbeformens materialer: *en simpel forarbejdningsproces*, *understøttelse af kompleks form*, *høj overfladekvalitet*, og *præcision*. Alle de undersøgte materialer bestred mere end to kvaliteter på bekostning af andre, afhængig af den anvendte forarbejdningsteknologi.

Ingen materialer, trods anvendelse af den mest egnede teknik, besad dog alle kvaliteter, hverken materialerne undersøgt i de emipirske studier eller case-studierne. Deraf kan konkluderes, at det med nutidens krav til ressourcebesparelser og konkurrencedygtighed er urealistisk at 'den ultimative støbeteknik' findes.

Endelig konkluderes det, at der for at frembringe tektoniske former i beton bør anvendes repræsentationsformer som beskriver arkitekturen som et resultat af frembringelsesprocessen, snarere end en storyline rodfæstet i formalistiske eller rent funktionelle foki, der fortæller en historie om arbitrære, ikke-eksisterende skridt der er taget mentalt, for at nå frem til en form. Arkitektur der udspringer af sådanne storylines fokuseres naturligt omkring de, oftest rent rumlige, emner der udfoldes hér. Dette kan undgås ved at være opmærksom på relationerne mellem materiale og teknik i frembringelsen af støbeformen før blikket rettes mod den egentlige geometriske form af betonkonstruktionen. Det vil sige: skabelsen af støbeformen bør gå forud for udviklingen af konstruktionen og have indflydelse på den arkitektoniske form.

SUMMARY

Contemporary techniques for concrete casting in an architectural context are challenged by demands of increased individualization in our built environment, reductions in the use of resources and waste generation. In recent years, new production technologies and strategies that break with the industrial paradigm of standardization, have been put forward. This development is carried forward by computers and digital fabrication, but has yet to find its way into the production of building components. With regards to concrete casting, however, existing research do offer advancement towards an increased customisation of casting moulds. The hypothesis of this research is that the techniques used in this research do not fully address the tectonic potentials of concrete which gives rise to the primary research question:

Is it possible to enhance existing or develop new concrete casting techniques which allows for individualisation and resource optimisation, while matching or enhancing the tectonic potentials found in existing, repetitive concrete casting techniques?

The research is comprised of two modes of inquiry: an *empirical study* of contemporary casting methods and subsequently six *case studies,* carried out as *research by design*. The empirical study is set forth to find tectonic implications and challenges in existing casting methods. These implications form the basis for the formulation of the case studies, the purpose of which is to assess tectonics potentials in existing casting techniques and develop novel ones. It is through an analysis of the empirical study and experimental case studies against a conceptual universe that conclusions are drawn and an answer to the research question is proposed. This conceptual universe is based

on research into established writings concerning tectonic thinking. The ideas of German Theorist Gottfried Semper are presented as a strategy for describing form as a result of materials and technical matter. Furthermore the idea of poetic construction are presented. Set forth by the english / american theorist Kenneth Frampton, the idea is that poetic construction is achievable though attention the properties of materials, structural logics and the craft of making. The thoughts of Marco Frascari which suggest a reading of *details* as a creator of meaning are introduced to be able to help establishing a progression in the case studies. Due to the narrow research focus on the *making* of concrete, an additional conceptual framework which emphasizes tectonics as a physical phenomenon is presented: The relationship between material, technique and form. Finally, a distinction was made between relationships surrounding mould making and the actual creation of geometric forms in concrete. The former was referred to as *mould tectonics*, the latter *concrete tectonics*.

A study of the concepts of *'New Production Philosophy'*, *'Mass-customization',* and *Digital Tectonics* is presented as a basis for investigating their use in concrete casting. Digital modelling and *simulation* as a mode of representation is presented as a means to contemplate both geometry and manufacturing processes at the same time.

In order to understand of the potential and problems in the investigated techniques a distinguishing between addition, subtraction, and transformation (A-S-T) is proposed. Addition is found to be the most widely used principle in contemporary practice, where the addition of Euclidian geometrical elements make up rectangular casting moulds which present a geometric restriction to the inherent isotropy of concrete. *Subtraction*, on the other hand, is found to be the most widely used technique for casting complex and amorphous concrete if resource minimization is wanted but all subtractive techniques currently developed suffer from poor surface quality.

Transformation is developed through casting in fabric which is found to contain a lack of precision which could become problematic when several fabric cast members are connected and in situations where fabric cast elements are to meet precise, rectilinear building components, such as windows and doors. This is addressed with the development of a novel casting technique using laser cutting and folding of large sheets of PETG plastic in which precision is maintained. The ability to reuse the PETG moulds makes the technique a zero waste production.

In general it was concluded that problems with existing techniques relate to production time, surface quality and precision and are caused by the use of mould fabrication technique and materials. These problems with the mould tectonic relationships are addressed in the case studies. The case study research gives rise to the conclusion that the logics of the technique should be a determining factor for the generation of form rather than a means to realise a preconceived form. This will reduce fabrication time and enhance a tectonic relationship insofar that the logics of technique becomes clearly expressed in the geometric form. Various design proposals are made to support this assumption.

The problem of poor surface quality of existing casting technique using Expanded Polystyrene (EPS) as a mould material leads to the finding that *casting* EPS under pressure against an adjustable membrane as opposed to *cutting* it, allows for amorphous concrete elements to be produced which have a high surface quality. This technique also dramatically shortens manufacturing time over existing techniques.

The successful design and construction of a research pavilion using the folded PETG plastic technique establishes that parametric and algorithmic computation support the generation of concrete structures which can respond to complex formational, material and contextual relationships. Provided these generative techniques are used in an iterative process, exploring boundaries rather than defining solutions. The Object Oriented design paradigm is found to support such development, allowing for structuring of code into ’classes’ such as: concept, geometry / material, and fabrication.

Based on an analysis of the empirical and case studies, four considerations essential to the mould tectonics are defined: *a simple process, amorphous form, complex form, surface quality* and *precision*. The mould materials examined are all found to possess more than two qualities at the expense of others, depending on the technique used. However, a single concrete casting material, given the use of the right technique that is able to address all these problems, has not been identified, neither in state-of-the-art nor in the case studies. It follows that due to today’s demands for resource optimization and competitiveness it is unlikely a ‘the one casting technique to end them all’ can be found.

Finally it is concluded that in order to conceive tectonic forms in concrete, the representational methods should be used to describe architecture as a result of its creation process. Not as a storyline rooted in formal or functional foci telling a story about arbitrary, non-existing steps that have been taken mentally to arrive at a form. Architecture that originates from such lines of thought naturally revolves around topics represented in that storyline, which is often purely spatial. This may be avoided by paying attention to the relationship between material and technique in the creation of the mould before turning to the geometrical form of the concrete construction. That is: the nature of the creation of the casting mould and the concrete elements should precede the development for construction and also influence architectural form.

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INTRODUCTION

This Ph.D. thesis is published as a part of the cross-institutional research project 'Towards a tectonic sustainable building culture'. The purpose of this project is to investigate and discuss tectonic potentials in a future building culture, with a special focus on sustainability. The pivotal aim is to establish a common, architectural research practice, based on a renewed theoretical foundation and suggest specific strategies for architectural design in a building culture undergoing rapid changes, and in doing so concentrate and strengthen the currently scattered research field in Denmark. Furthermore, the aim is to make the research available to practitioners and other research projects, both in Denmark and internationally. The project has two central research questions:

a) Is it possible to strengthen a tectonic building culture through new fabrication processes , in which the resources are used in amore qualified and deliberate (and systematic) manner?

b) Which new initiatives are required, if we are to develop a strong, tectonic building culture, taking the growing climate and environmental problems into consideration?

Within 'Towards a tectonic sustainable building culture' there is a 'main project' and four 'sub-projects'. The main project conducts fundamental research into tectonics, sustainability and building culture and is undertaken by Professor, Architect Karl Christiansen, Associalte Professor, Architect, Charlotte Bundgaard from the Aarhus School of Architecture and Professor, Architect Anne Beim from the Copenhagen Royal Academy of Fine Arts.

Each of the four sub-projects investigates a specific problem within this field.

Professor, Arkitekt Claus Bech-Danielsen investigates possible strategies for performing a transition towards climate adapted architecture.

Arkitekt, Lecturer Ulrik Stylsvig Madsen investigates the building as a resourceful and dynamic structure.

Associate Professor, Architect Thomas Bo Jensen investigates possible future tectonic uses for bricks in architecture.

The last of the four sub projects is 'The tectonic potentials of concrete'.

PART I - RESEARCH TOPIC

Figure 1. Ordos, a new Chinese city in the inner Mongolia

CHAPTER 1: RESEARCH QUESTION AND METHODOLOGY

CONCRETE IN OUR BUILT ENVIRONMENT

Concrete is the most widespread material in the contemporary building practice. Its content of available natural resources, constructive strength and durability makes it a cheap and reliable building material, suitable to be put to use in many tasks within architecture.

At the same time concrete – in the current way it is produced and used - poses environmental, formal and technological problems.

The environmental problem is that the production of concrete is tied to a large use of resources and generates an enormous amount of waste products. These are CO_2 from the burning of chalk which makes up 5% of the world's total CO_2 emission[1], but also waste out-let of gasses and materials from creating the moulds. Scientific reports stress the importance of using the earth's natural resources with thought and minimizing the volume of harmful waste products. [2][3] Thus a need to cast concrete in ways that have the least possible impact on the environment has arisen.

From an environmental point of view, the repetitive concrete elements used in the current building practice do not meet these criteria. Despite their standardized appearance, elements are often cast with small differences – an extra window, a ventilation duct outlet, a console for attaching other building components[4]. This is why buildings made from concrete elements require the production of casting moulds which are only put to use a limited number of

1 Adrian Forty, *Concrete and Culture - A Material History* (Reaction Books Ltd, 2012), pp. 70–71.

2 Gro Harlem Brundtland, *The Brundtland Rapport* (United Nations, 1987).

3 *IPCC Third Assessment Report - Climate Change 2001* (IPCC, 2001).

4 Karl Christiansen and Anders Gammelgaard Nielsen, 'Industrialiseret Individualitet', Arkitekten, 2006, 55–59.

Figure 2. The Bella Sky hotel in Copenhagen under construction. By Danish Architects 3xn.

times before being thrown away. Furthermore, the concrete used is not materially optimized in any way, resulting in more concrete being used than is necessary structurally.

Concrete also has a bad name in the way it presents itself in the built environment, due to the innumerable buildings created in repeated and standardized concrete elements. In 1981, the architectural theorists Alexander Tzonis and Liane Lefaivre presented a criticism of the lack of identity in globalized, modern architecture under the name 'critical regionalism'[5]. The thoughts were elaborated by Kenneth Frampton in the article *Prospects for a Critical Regionalism*, published in 1983:

"The phenomenon of universalization constitutes a sort of subtle destruction, not only of traditional cultures, [...] but also of [...] the creative nucleus of great civilizations and culture, that nucleus on the basis of which we interpret life [...][6]

Frampton argued that buildings which are conceived without influence of place and culture lack the ability to enter a dialog with their surroundings and actually wash over qualities of place and region with an unfortunate, alienating international style. The new settlements in the rapidly growing economies in Asia may serve as contemporary example of this problem (figure 1).

Cultural and historical factors, personal preferences and the wish to build according to qualities of a given place have resulted in an backlash against the commonly used, repetitive forms.[7] Where the brief and budget allow, architects try to apply a degree of individuality to concrete architecture. This is evident where the standardized concrete elements

5 Alexander Tzonis and Liliane Lefaivre, 'The Grid and the Pathway. An Introduction to the Work of Dimitris and Susana Antonakakis', *Architecture in Greece*, 1981.
6 Kate Nesbitt, *Theorizing a New Agenda for Architecture* (Princeton Architectural Press, 1996), p. 470.
7 Stephen Kieran and James Timberlake, *Refabricating Architecture* (McGraw Hill Professional, 2004), p. 109.

are placed in varied formations to mask the appearance of repetition.

The backlash against repetition has also affected the attitude towards the material concrete itself in a negative way and it is rarely allowed to serve as the cladding of a building, even though concrete is one of the most durable and weather proof materials available. Typically the actual house in concrete is hidden behind an additional façade that is applied in a different material, increasing the resources needed (figure 2) and the complexity of contemporary architecture. In short, the architectural potentials that lie in working actively with material characteristics and a structural reading embedded in architecture are eliminated.

In the recent years new production technologies and strategies that breaks with the industrial paradigm of standardization, have been put forward. The development is carried forward by computers and robotics, but has yet to find its way into the production of building components. Today individualized moulds are rarely used and the formal implications within the mould materials and the technology used to produce the moulds are not put to use. As a consequence, producing individualized concrete elements becomes advanced, resource-demanding and expensive. All are factors that disqualify mass-customized concrete panels as an alternative to the current production of repeated concrete elements.

RESEARCH QUESTION

Standardization and the use of repetitive production processes was a key determinant of achievable forms in the pre-CAD and pre-CAM industrial paradigm. Furthermore, the representational and geometric limitations of analogue drafting and orthographic projection were as significant as material constraints in the delimiting of formal possibilities[8]. Today, advances in 3d modelling and scripting techniques allow the drafting of complex form.

8 Representational strategies in the 20the and 21th century and the consequence for generation of forms in concrete are assessed in chapter three.

Computer-controlled design and production techniques allow for the subsequent panelization and fabrication of complex non-repetitive elements that approximate the forms. If technology is not an integral part of the design process, however, designs tend to become overly complicated, resource demanding and expensive. These considerations give rise to the primary research question:

Is it possible to enhance existing or develop new concrete casting techniques which allows for individualisation and resource optimisation, while matching or enhancing the tectonic potentials found in existing, repetitive concrete casting techniques?

This question leads to secondary questions: Is it possible to identify concrete casting techniques in which there is a closer connection between the material, the technology and the form of the concrete element than is the case today? And, in doing so address two problems in the current production of concrete elements: the lack of connection between the intention of creating variation in our build environment and the current ways of shaping concrete elements. And the environmental challenges, which primarily call for a reduction in waste products generated in the production of concrete elements. How can modern technology uncover or reveal the formal potentials of concrete, creating concrete with a high architectural value while maintaining a production line that is environmentally sustainable? The question leads to the hypothesis that:

...by taking a starting point in the term tectonics and the modern technological situation, new industrialized methods of producing individualized concrete elements, can be developed. Methods which are capable of competing with a traditional production of standardized elements and at the same time have an inherent, added architectural value and a better environmental profile.

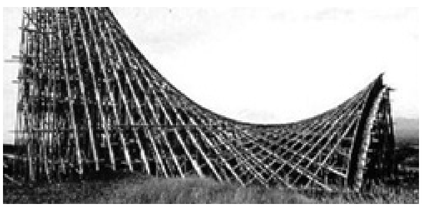

Figure 3: Falsework for a concrete shell construction by Felix Candela.

EXISTING RESEARCH

Several complex concrete structures have been developed and built in the 20th century by architects and engineers such as Pier Luigi Nervi[9] and Felix Candela[10]. These projects were all time and resource demanding, and required large amounts of timber formwork to be constructed. The designs could be described in terms of basic geometry in order to ease production of this formwork. Such casting principles are rare today because in-situ casting is costly and it is easier to achieve high precision and high quality concrete when casting elements in a controlled environment. Also, despite their inherent complexity and fluidity, the need for a repetitive geometry limits the ability to adapt such construction principles to different situations.

Research undertaken from 1998 to 2010 (figure 4) investigate how complex concrete structure can be made with the use of fewer resources. These projects may be described in two categories:

The first category is concrete cast using a minimum of formwork, utilizing the concrete's weight to generate form. The Canadian research unit C.A.S.T has developed this trajectory by using fabric formwork[11]. The second category is the use of computer-controlled manufacturing for the production of formwork, investigated in the Danish research projects: "Unikabeton", "Industrialised individuality", "Tailorcrete", and "AdaptiveMould".[12]

RESULTS

This project takes as its starting point these state-of-the-art projects and investigates the tectonic implications as a basis for further development. The goal is to identify potentials and challenges in working with concrete technology as part of a viable tectonic building culture, exemplified with a series of

9 Pier Luigi Nervi, Aesthetics and Technology in Building (Harvard University Press, 1965)

10 Maria E. Moreyra Garlock and David P. Billington Sr, Felix Candela (Princeton University Art Museum, 2008)

11 West, M. 2009. Thin Shell Concrete from Fabric Molds. http://www.umanitoba.ca/cast_building/assets/downloads/PDFS/Fabric_Form work/Thin-Shell_Concrete_From_Fabric_Forms_SCREEN.pdf. Accessed 14 May 2012

12 Recent research into novel concrete casting techniques with tectonic implications is assessed in chapter six.

2010 AdaptiveMould
Flexible casting table
ADAPA (company)

2009 TailorCrete
Re-usable formwork, Robotic-bent reinforcement.
Teknologisk Institut

2007 Industrialized Individuality
Hotwire cut EPS formwork, surface treatment
Aarhus School of Architecture

2006 Unikabeton
casting in CNC milled EPS
Aarhus School of Architecture / Teknologisk Institut

1998 C.A.S.T.
Fabric Formwork
Univeristy of Manitoba

syntax:

YEAR PROJECT NAME
FOCUS
INSTITUTION

Figure 4: Timeline of recent research projects investigating the making of complex forms in concrete

cast experiments. These experiments present a proposal for specific developments of today's concrete production by exploring the tectonic potentials in the making of formwork and castings using the newest technologies.

On a general level the results include a method for identifying and developing tectonic parameters in concrete casting techniques, meant to be a tool for academics and professionals in the future development of casting techniques in architecture.

METHODOLOGY

The research is comprised of two modes of inquiry: an *empirical study* of contemporary casting methods and subsequently six *case studies*. The empirical study is set forth to find tectonic implications and challenges in existing casting methods. These implications form the basis for the formulation of the case studies, the purpose of which is to assess tectonics potentials in existing casting techniques and develop novel ones.

It is through an analysis of the empirical study and experimental case studies against a theoretical framework that conclusions are drawn and answers to the research question is proposed. This framework is established as an account of relevant theories needed to support the analysis and discussion.

The casting methods described in the empirical study stem from the research context with emphasis on methods which have potential for resource optimization, and their potentials for being part of a mass-customized, automated, industrial production.

The word *case study* is used to cover both investigations into how realisations can be achieved from working hands on with existing casting principles and experiments where novel casting methods are developed and analysed. The findings in the empirical studies form the basis for defining six case studies, in which one or more potentials or challenges are addressed.

A transparent and systematic process as well as systematic evaluation for the description of the interventions is needed. It is necessary to structure the theoretical, ideological, aesthetical and ethical considerations that lead to the intervention with, or observation or judgement of a case.

This project is based on 'research though design' (RTD), a commonly used research method for investigations within the field of architecture and design, also referred to as practice-based research[13]. RTD is a method that accounts for the fact that the process is an important part of the research outcome and as such is not only a means to achieve a goal, as is the case in other types of research. The method is used to ensure transparent results, even though the nature of conclusions differs from those obtained by traditional principles for valid research. The English theorist Christopher Frayling describes the method as one where the *development itself* is a part of the research result.[14]

13 Stephen Scrievener, 'Characterising Creative-production Doctoral Projects in Art and Design', *International Journal of Design Sciences and Technology*, 2002, pp. 25–44.
14 Christopher Frayling, 'Research in Art and Design', *Royal College of Art Research Papers*, 1993 (1993), p. 5.

STRUCTURE OF THE CASE STUDIES

Knowledge is built within the case studies by means of observing, describing and evaluating the work. Given the RTD mode of inquiry, this knowledge is not a result of problem solving, but rather a wondering, such as: 'How can it be that...?' or 'why is...?' By creating something new or a connection between existing and new, a new meaning of the observed is "designed", as mentioned not only of the result, but also of the process. This is also called *reflection through design*.[15] This point towards a progression in, or ordering of, the cases where the first cases are investigations firmly rooted in existing research, allowing a foundational knowledge of the field. Subsequent cases present an increasing degree of autonomy or novelty, influenced by the experience gained in the previous work. This *gaining of experience* which influences and interferes with later cases may be of a subjective nature: some casting principles may have greater aesthetic potential than others. In order to be able to qualify the development as research, a justification or examination of the use of subjective considerations is presented in chapter two. That being said, the experiments are not to be regarded as design objects for their own sake, or just for the sake of creating form. The purpose of experimentation is to create a space for reflection over the research questions.

It is essential that the cases are not reduced to verification, conversion or an updating of existing casting solutions or concepts, but rather that they are novel in character, and spur new experiments based on tectonic implications, taking the experiments in new directions. In other words, the cases need to challenge existing thought and understanding of technology and concrete construction. This requires a special focus on the act of generating form itself, which in the case of concrete casting happens by means of *the mould*. Hence, the cases need to examine a specific understanding of tectonics concerned with creating the mould. That is: the materials, technologies, and the resultant form when creating the moulds. Here, it is possible to look both at the individual topics, for example the characteristics of a material, or to look at

15 Richard Blythe, *Notes on Design Research* (RMIT University Melbourne, 4 April 2010), pp. 5-8.

the relations between them, for instance the relation between a material and a technology.[16]

CONCEPT CLARIFICATION

The word *mould* or *casting mould* is used throughout the thesis to describe the cavity in which concrete is cast. The word formwork is generally avoided because it is usually refers to the complex moulds used for casting concrete in-situ.

16 This definition of tectonics as a relationship between material-technology-form is accounted for in the chapter ’The Foundation of Tectonics’.

CHAPTER 2: FOUNDATION OF CONCRETE TECTONICS

In order to create a basis for experimentation, the establishing of a theoretical framework is needed. The term 'tectonics' is able to provide In the following a brief introduction to the term tectonics is offered. The introduction is divided into two parts: Firstly seminal writings and research concerned with tectonics are presented. Then, a more personal attitude to tectonics and aesthetics is offered.

TECTONICS

As described in chapter one, an experimental approach to the enquiry into the tectonics potentials is chosen. This calls for the establishment of a theoretical framework which may be operationalized and guide progression of the experiments. That is: explain choices made in the experimentation, or serve as evidence or example when claiming a certain quality of a concrete casting technique. This chapter unfolds the term *tectonics* as a such a framework, with emphasis on a account of tectonics which provide the most 'active' assessment of the term: tectonics regarded as an attitude to the action of 'bringing forth'. Hypothetically, this allows for a transparent and understandable link between theory and case studies. A back draw, however may be that the conclusions and subsequent discussion will become less rich, if certain views on tectonics is omitted. A more elaborated conceptual universe regarding tectonics can be found in the book 'Tectonic Visions in Architecture by Professor, Architect Anne Beim.[1]

1 Anne Beim, *Tectonic Visions in Architecture* (København: Kunstakademiets Arkitektskoles

According to the British/American historian Kenneth Frampton Tectonics originates from the Greek tekton, which means carpenter or builder. In the fifth century gained a broader meaning as it was used to describe the act of skillfully making artifacts by means of treating materials2 This included both the specific craft and creation of art at the same time, a duality which is found in the historic assertions as well as contemporary views on tectonics.

In the 19th century influential architects did research into tectonics based on studies of ancient handicrafts and construction. Karl Bötticher's *Tektonik der Hellenen*[3], published in 1852 advocates that the generation of architectural space and form should derive from a structural logic. Bötticher was afraid a too philosophical approach to architecture would lead in the direction of arbitrary forms. Instead he proposed a new way of seeing ornament as something intrinsic, derived from material logics and structural forces. Bötticher's work was primarily an account of the history of art, revolving around ancient Greece. A research paper investigating the nature of Bötticher's research note that the focus on *ornament* in mid 18th century Germany influenced his thoughts[4]. As a result, the paper suggests, Bötticher's writing Tektonik der Hellenen takes interest in formalistic conception of tectonics, and serves as an introduction to the architecture of the Greeks.

The thoughts on the relationship between ornament and structure also occupied the German Architect and Theorist Gottfried Semper. In *The Four Elements of Architectu*re[5], from 1851 Semper proposed a dictonomy which includes actual building components such as *frame* and *earthwork*[6], which is why his ideas provide a solid basis working with tectonics in this context.

Forlag, 2004).
2 Kenneth Frampton, Studies in Tectonic Culture: The Poetics of Construction in Nineteenth and Twentieth Century Architecture (The MIT Press, 2001), pp. 3–4.
3 Karl Boetticher, Die Tektonik Der Hellenen (Riegel, 1852).
4 Susan Jones, 'The Evolving Tectonics of Karl Bötticher. From Concept to Formalism', Conference Proceeding for International Architecture Conference Tectonics: Making Meaning, 2007.
5 Gottfried Semper, The Four Elements of Architecture, 1851.
6 This reading of Semper is based on Frampton op.cit. p. 5

SEMPER: ARCHITECTURE AS IDENTIFIABLE ELEMENTS

Semper describes certain *elements* that are essential to architecture and which have their own intrinsic logic in terms of use of materials and construction techniques – and the correlation between these. On the basis of a thorough analysis of traditions in ancient Hellenic and Mediterranean cultures, Semper traces and categorizes the physical manifestation of these cultures to modern times, proposing that architecture consists of four elements. While a direct reading of these elements into modern times may be interesting in itself, the implications for an assessment of tectonics as a term lies in the way Semper describes now developments in material properties, construction techniques and cultural circumstances have influenced the *form* of each element.

In The Four Elements of Architecture, Semper present an anthropological study of the origin of walls, leading to the definition of the phenomenon *the enclosing membrane*[7]. Derived from ancient ways of living, Semper argues, the closing membrane is originally screens made of woven carpets or wickerwork. This enclosing membrane is detached from the *frame or framework* which, Semper suggests, are the matter of other materials and techniques, namely wood and woodworking. Originating from ancient vernacular architecture, an understanding of contemporary architecture as a composition of the four elements may not be the most fruitful use of Semper's theory[8]. It is the idea of viewing architecture as identifiable elements, which come into being because of technical factors and other factors that are fruitful. The English architect and historian Kenneth Frampton argues a difference in the Vitruvian triad of *utilitas*, *firmitas*, and *venustas* and Semper's four elements of architecture. Vitruvius, Frampton argues, describes architecture using adjectives - thus stating the *values* of it, while Semper can be said to introduce an attention to the *properties* of an architecture consisting of physical elements which carry cultural meaning, functional justification, as well as material and techni-

7 Semper, pp. 104–105.
8 As noted by Kenneth Frampton in Studies in Tectonic Culture (pp. 6-7)

cal logic[9]. Put differently, the architectural elements have not come into being as just the result of abstract considerations such as proportions and symmetry. Rather, a continuous evolvement of technological, resource and material practices constitutes their presence. This makes Semper's thoughts useful in a research context insofar that they provide a strategy for describing form as a result of materials and technical matter, among other factors.[10]

FRAMPTON AND THE POETICS OF CONSTRUCTION

An elaboration of Semper's thoughts is offered in '*Studies in Tectonic Culture*'[11]. In a criticism of the scenographic character of postmodern buildings, Kenneth Frampton argues that *construction* encompasses cultural and poetic meaning. The concept of 'space', Frampton argues, has had a predominant role in architectural discourses in the 19th and 20th century[12], at the expense of tectonic thinking. The notion of space is put into perspective by reconsidering the role of *structure* and *construction*. Not in favor of space, but as important factors in the creation of space, as stated in the introductory remarks:

> *'It is my contention that the unavoidable earthbound nature of building is as tectonic and tactile in character as it is scenography and visual, although none of these attributes deny its spatiality'* [13]

To investigate the nature of building Frampton gives an etymological analysis of the word tectonics and a historical account of its use by architectural theorists, starting with Semper and Bötticher. He then advances to provide examples where tectonics plays an important role in the creation of space: works by Frank Lloyd Wright, Auguste Perret, Mies Van der Rohe, Louis Kahn, Dimi-

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9 Frampton describes "The four elements of architecture" as a fundamental break from the Vitruvian Triad. (Studies In Tectonic Culture p. 85)
10 The Four Elements of Architecture pp. 74-127
11 Frampton, op.cit..
12 Frampton, op.cit. p.2 Exemplified by Frampton with Schmarcow (1893), Lobachevsky through Riemann, Gideon, Einstein, to Cornelis de Ven (1978)
13 Frampton, op.cit., page 2

Figure 1: Taliesin West by Frank Lloyd Wright

tris Pikionis, Alvar Aalto, Jørn Utzon, and Carlo Scarpa. These examples, Frampton argues, succeed in rooting the building design in the fundamental parts of architecture as opposed to importing ideas from figurative fields or philosophy. As such the works serve as counterexamples to ideas of space considered as representation of economic, stylistic or purely symbolic matters, detached from fundamental considerations of materiality, the process of building, and the *genius loci,* the spirit of the place. Notably, Sydney Opera House by Jorn Utzon is presented as an example which establishes a relationship between earthwork (the base) and a tectonic frame (the shells which represent the roof work)[14]. A specific project, also build with concrete, further illustrate Frampton's thoughts: Frank Lloyd Wright's Taliesin West near Phoenix, Arizona (figure 2). A

14 David Leatherbarrow, 'Journal of the Society of Architectural Historians', 56 (1997), 98–100.

reading of nature, topography, and materiality of the site is the origin for the building in in-situ cast concrete, where the low, long lines of the walls suits the casting technique while relating to the landscape. The adding of local sand and stones to the concrete mix further emphasizes this relationship between the process, site, and construction. Both the Sydney Opera House and Taliesin West are illustrative examples of an emphasis on two of Semper's four elements found with Frampton: the topological mass (the earthwork), and the tectonic frame.

Frampton's thoughts are useful as a means to describe how constructive logics which accompany certain casting methods may point to formal, functional, and spatial strategies of a tectonic architecture in concrete: *coherence* between a form and its origin. As such the idea of the poetic construction may be used to initiate inquiries which interconnect a certain constructive logic and a casting technique and to suggest the constructive - hence architectural - perspectives of a particular casting technique.

FRASCARI AND THE ATTENTION TO DETAILS

An elaboration of designing constructions and the process of building is found in the paper "The Tell the Tale-Detail" by Marco Frascari[15]. Tectonics is not used as a offered as a term in the text, but the discourse proposed represents a similar way of thinking, in that it suggests material and constructive considerations as a generator of form[16] – somewhat in opposition to the Modern idiom of using the plan as the generator of form as proposed by Le Corbusier[17] - or the late modern one of the building as diagram, as promoted by Gilles Deleuze[18] and Rem Koolhaas of OMA[19].

Frascari presents the *detail* as a union of construction with construing (or interpretation) of architecture. The detail is understood on different levels and thus not only as a physical object isolated from its context. Based on a

15 Marco Frascari, 'The Tell the Tale Detail', *Via (1984)*, 23–37

16 A similar view is offered by Eduard Sekler in the writing "Structure, Construction, Tectonics" (Sekler, E. F., Structure, Construction, Tectonics, in ed. Kepes, Gyorgy, Structure in Art and Science, Studio Vista, London, 1965.)

17 Le Corbusier, *Toward An Architecture* (Getty Publications, 2007), p. 87.

18 Gilles Deleuze, *L'Anti-Oedipe* (Paris: Ed. De Minuit, 1975), chapter one.

19 Rem Koolhaas and others, *S, M, L, XL* (Crown Publishing Group, 1998).

theoretical assessment of details and an empirical study of the works of Carlo Scarpa, "detail" is established as a significant part of architecture as an art. The study concludes that the act of detailing, or the establishment of an *order of detail,* in turn affects the *order of the building*. This is due to the fact that details play a central role in avoiding building failure and in handling the joining of different materials, components and building parts, in a manner that is both functional and aesthetical. Frascari states:

"[...] In the details are the possibilities of invention, and it is through these that architects can give harmony to the more uncommon and difficult or disorderly environment generated by culture."[20]

Frascari proposes that the detail holds a duality insofar the *joints* refer to both the *actual* joint, concerning practising of workmanship, and the *formal* joint which is the detail as 'the minimal unit in the process of signification': an important part of understanding the built environment. The joint, Frascari argues, is where not only *construction* but also *construing* of architecture take place, since haptic and visual sensory inputs directed at details are read against our minds' conventions of what is space, order and structure, hence they give meaning to the perceived.[21]

The question arises if Frascari's thoughts regarding signification can be applied to the casting process. This will be a focal points in the attention to details in the case studies: The attempt to express construction logic which in turn may provide clues for tectonic potentials and hence the aesthetic values of a given casting technique.

20 Frascari, op.cit. p. 24.
21 Frascari, op.cit. p. 28.

TECTONICS AND AESTHETICS

On the basis of the on a here presented framework of tectonics, it is deduced that certain subjective considerations play a central role when investigating the tectonic potentials of concrete. Frampton emphasizes the *genius loci*, the spirit of place, and cultural and poetic meaning. Frascari introduces an *order of the building*. These are all topics which deal with aesthetics and phenomenological aspects in construction and detailing While it is outside the scope to present a comprehensive account of aesthetics in architecture, some remarsk with regards to dealing with aesthetic value in architectural research are offered.

An opinion on the relationship between humans and the world in a modern, industrialised society is offered by Martin Heidegger[22]. Heidegger warns about a positivist approach to technology, where technology is used to achieve a maximum output from resources (nature). This view on technology, Heidegger argues, allows for only one mode of truth, one *revealing* among others which are suppressed. Heidegger proceeds to suggest an alternative way of using technology in symbiosis with material and resources, pointing towards a more nuanced causal relation between a form or an idea and its execution.[23]

If Heidegger's arguments are accepted, then what is needed to enrich our world are ways of using technology that allow for truths which are more than strictly scientific or formal. In this case: the creation of concrete constructions that come into being not only as an answer to optimisation processes or functional demands, but as means of enriching our build environment; in other words, as *art*. Heidegger proposes that a precondition for art is the work, which comes into being as a result of *creation from bringing forth* – something which requires craftsmanship[24]. Heidegger argues that the *work*, insofar that it is a work of art, contains a *truth:*

22 Martin Heidegger, *The Question Concerning Technology, and Other Essays* (Garland Pub., 1977).

23 Heidegger, *The Question Concerning Technology, and Other Essays*, pp. 44–51.

24 The Origin of the Work of Art. In Martin Heidegger, Basic Writings: Martin Heidegger (Taylor & Francis Limited, 2010), pp. 182–185.

CHAPTER 2: FOUNDATION OF CONCRETE TECTONICS

To create is to let something emerge as a thing that has been brought forth. The work's becoming a work is a way in which truth becomes and happens.[25]

This truth is different from the truth found in natural sciences, because subjective, aesthetic realisations act as evidence in the making of decisions, evaluations and reflections. Hence the mechanism of proving or justifying assumptions is also different from the mechanism used in natural sciences.

Furthermore, it can be argued that a specific method of inquiry, not rely solely on the hypothetico-deductive method,[26] is needed, because the hypothesis may be impossible to falsify or verify in terms of true conclusions. This is true at least if it is accepted that the tectonic qualities of a physical manifestation has to do with its phenomenological and aesthetic features . Certain pointers indicate whether this is the case (public acclaim is one such pointer), but it can never be established as a true conclusion. Put differently, the research needs a basis for evaluation dealing with aesthetics. Even though no true conclusions, in the sense used by natural science, can be made, it is still required that the research has actual findings: that a means for proving the assumptions is proposed. Experiments carried out as research by design involves a progression that relies on design decisions, which necessarily have to be evaluated on the basis of aesthetics[27].

In the introduction to the book: Knowing Art: Essays in Aesthetics and Epistemology[28], the authors Matthew Kieran and Dominic McIver Lopes present the complex issue of 'knowing through art'. Aesthetics is presented as a means to achieve realisations[29] of epistemological value: a certain mood or experience that art produce within the individual, may become knowledge in the sense that it helps to define this person. This cognitive paradigm, it is noted, that

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25 Heidegger, op.cit. p. 185.

26 Relating to the testing of the consequences of hypotheses, to determine whether the hypotheses themselves are false or acceptable (Oxford dictionaries)

27 The term Aesthetics is established by Alexander Baumgarten as '[...] the science of sensual cognition' (qouted in Hammermeister, 2002, 7).

28 Matthew Kieran and Dominic McIver Lopes, *Knowing Art: Essays in Aesthetics and Epistemology* (Springer Science+Business Media B.V., 2006).

29 Realisation means to describe the acceptance of something as a fact or to begin to understand. (Oxford Advanced Learner´s Dictionary).

can be traced back to Aristotle, who argued that the Greek tragedies made a significant contribution to the knowledge and culture of the Greek people. Kieran and Lopes specify that the definition has been met with criticism; an opposition between aesthetics and knowledge, set forth by Plato and Leo Tolstoy among others. They structure this criticism in *four challenges* that will be discussed here in relation to the specific methodology used in the inquiry.[30]
In these answers *aesthetic justification* can be found. That is: certain qualities which are important for something to be of aesthetic value and may serve as points for justification when findings are claimed to have architectural potentials.

1. THE TRIVIALITY CHALLENGE

The first challenge is called the *triviality challenge* and takes its starting point in a claim: art is a propagator of trivial and banal truths and thus unable to bring forth new realisations. The argument behind this claim is this: unless art is a mirror of reality, we cannot use it to say something true about reality. Art is bound to be a matter including the imaginary to serve its purpose: to enable us to think beyond the boundaries of the real. The challenge is met by Heidegger's claiming that the outcome of the encounter with a piece of art has a phenomenological value, which spurs new lines of thought, ultimately leading to new realisations. For this to be true the piece of art must fulfil certain criteria to inaugurate these lines of thought. The American Philosopher Nelsen Goodman addresses this by saying there exist certain 'aesthetic symptoms' which can be found in a work of art if the work has a semantic density or fullness to it.[31]

2. THE WARRANT CHALLENGE

The second challenge is the *warrant challenge*, arguing that knowledge requires warrant, which art and architecture is unable to supply.

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30 Kieran and Lopes. Op.cit. Introduction pp. xi-xviii
31 Dominic McIver Lopes and Berys Gaut, The Routledge Companion to Aesthetics (Routledge, 2005), pp. 194–495.

A hypothetical situation may illustrate the challenge: A case study arrives at the conclusion that it is possible to fabricate complex concrete elements, the shape and constellation of which establish a dialogue with their context. Simultaneously the elements are a result of a qualified use of the applied technique and mould material. A series of drawings, photos, of models were produced to illustrate how this (imaginary) structure had aesthetic qualities because of the dualistic origin of form (originating from both a reading of the landscape and the technique). It would be impossible to warrant this claim.

The answer to the challenge must be found somewhere else, in another argument, attacking the relevance of the challenge in the first place: It can be argued that it is pointless to even discuss warrant as a physical fact when the subject of evaluation is within the realm of architecture, because the warrant – or the grounds for evaluating the phenomelogical and aesthetical aspects of architecture – is to be found in the experiences that architects and artists accumulate through years of studying and practise. Since these experiences qualify architects to draw such conclusions, it is the premise of that challenge; the claim that warrant in a sense that it is used in natural sciences, should apply to architecture, that is wrong.[32]

3. THE UNIQUENESS CHALLENGE

The third challenge, the *uniqueness challenge* questions the absence of methods by which knowledge can be subtracted from the work. Every piece of architecture is unique and came into being by means of its own unique method, regardless of the limitations that apply to other fields of research. The challenge can be met partly by claiming that it is actually possible to describe the methods used in architecture, but on a more general level than is the case in natural sciences. The method, research by design is an example. Another argument, which is perhaps more valid, is that it is impossible to talk about just one correct method for achieving aesthetic realisations. Hence the methods

32 Kieran and Lopes. Op.cit. p.xiii

used in this thesis – research by design, tectonics as a qualifying term, etc. are not to be seen as the only way, but as one amongst other equally valid methods.[33]

4. THE RELEVANCE CHALLENGE

The fourth and last *relevance challenge* claims that new discoveries, in which aesthetic realisations are an important part, do not necessarily lead to generation of knowlegde. The answer to the challenge is that architecture as a profession has the potential to act between aesthetic values and cognitive contents. An example of this is the open work[34] and the user´s influence on the architecture. Another answer, which is more relevant to this project is the use of the term tectonics, which encompasses the notion that aesthetic quality can occur when one or more materials are treated and assembled, forming architecture, in a way that serves a purpose (adds to knowledge about how we may build), while containing a narrative about the material properties, the applied technique and a certain constructive logic.[35]

If it is accepted that results of the research are not answers to a hypothesis which can be confirmed of falsified in the sense used in classical science, the triviality-challenge is irrelevant altogether.. Then the results would not be answers but source of inspiration for the individual to consider. This would, however, be an unacceptable disclaimer if the findings merely echoed already experienced conditions. In order for the research to become relevant, the basis for having new experience and understanding, needs to be present.The results are only relevant answers if the thesis succeeds in presenting artefacts or findings that escape being a mere reduction to or confirmation of, what we already know; or findings that are too abstract and uninteresting to invoke exactly that reaction in the individual, leading to reflection and understanding. Put differently, the experiments will have to be evaluated against state-of-the-art, and the work is only relevant when analysis shows that there are findings that with

33 Kieran and Lopes. Op.cit. pp.xiii-xiv
34 Umberto Eco, The Open Work (Harvard University Press, 1989).
35 The four challenges are described in the book " Essays in Aesthetics and Epistemology" where the authors Matthew Kieran and Dominic McIver Lopes describe challenges as well as answers on a general level.

certainty can be said to present something new, something imaginary.

MATERIAL-TECHNIQUE-FORM

The answers to these four challenges illustrate that art and architecture when considered as art is complex because a central part of it deals with several layers of meaning. But when creation takes place in an architectural context, some basic preconditions may be established. A description of such preconditions is offered in the article ‘Arkitektur – Form og Teknik’ (Architecture – Form and Technique)[36] by Professor Architect Karl Christiansen. In the article three fundamental relations, ones that cannot be removed if one is to be able to describe something as architecture. The three elements are referred to as an *axiom* of architecture. This definition emphasizes tectonics as a physical phenomenon. As noted in the beginning of the chapter, other layers of meaning and a higher degree of complexity which may also be associated with tectonics is omitted here.

MATERIAL

The presence of deliberate form assumes the presence of a the physical manifestation of this form – a *material*. Again this material must be treated in one way or the other to be lifted up from the realm of nature, into the realm of culture.

TECHNIQUE

Technique is defined in the Oxford Dictionaries as: (“a way of carrying out a particular task [...] of an artistic work [...]. More specifically: A skilful or efficient way of doing or achieving something. C*onstruction*, which Frampton associates with tectonics in the phrase ‘poetics of construction’, is arguably related to technique. And so is *technology*, which is understood by Frascari as a complex matter concerning both theory and practice related to architectural production[37].

36 Karl Christiansen, ‘Arkitektur - Form Og Teknik’, Arkitekten, Arkitekten, 1995.
37 The statement regarding technology in relation to tectonics is based on Beim, op.cit. p. 46.

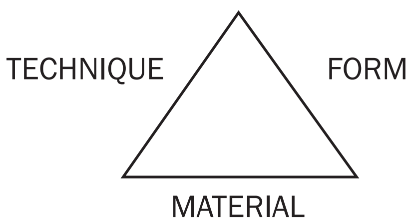

Figure 2: The M-T-F triangle

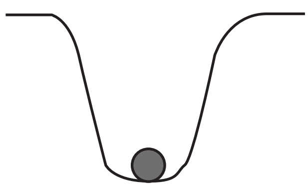

Figure 3: giant's pot

FORM

Thirdly, there has to be a *form*, a deliberate form, if something is to be called architecture. If the form is not deliberately made by humans, it is not architecture but nature.

These three elements: a *material* (M), subjected to a *technique* (T), to present a *form* (F), is the core of tectonics. The interdependency may be illustrated by placing M, T, and F in a closed relationship, where each element is connected to the other two: in a triangle (figure 2)[38].

But this is not all; not every man-made form can be said to be tectonic. There has to be a *relation* between the form, technique and material. We get such relations in nature, which is a good example of how matter and form can be coherent – simply because the 'technique' of nature is automatic, it knows no other way. It is a process like in the Giant's pot (figure 3).

The example allows us to think about the material and technique: the stone that is ground by the flow of water. The form: the concave shape of the cliff and the gradual rounding and size reduction of the stone that is unable to be washed away.

The processes happen simultaneously and all represent both cause and effect: a closed M-T-F relation is established.[39] Interestingly, we can establish similar situations in architecture. Here the task of building becomes more inclusive than building for a function – is also about *telling a story through form*, as suggested by Aristotle.

In the Simpson Lee house by Glenn Murcutt (figure 4) the deliberate form – or construction, plays a key part. The steel generates a boundary between outside and inside. It is subjected to a technique that shapes it into sine curves, which is necessary for such a thin plate to cover a large area without buckling. The tension wires are necessary for static pur-

38 Christiansen, 'Arkitektur - Form Og Teknik'.

39 Karl Karl Christiansen, *ArkitekturKunstruktioner*, 1994, p. 26.

Figure 4: Glenn Murcutt: Simpson Lee House

poses – to keep the frames rigid. Something happens – because of the relationship between the material, technique and form, an extra layer is added – the shadow from the stringer that plays on the curved steel plate (figure 5).

TECTONICS AND CONCRETE CASTING

When asking the question "what is tectonic concrete casting?" one actually asks about the tectonics on two levels of pertinence, due to the fact that concrete castings are an imprint of a mould, which imply two processes: namely the concrete casting and subsequent assembly of concrete structure, but also the actual making of the mould. These two levels may be illustrated as concerning the making of forms with concrete, that is: The actual *building* (the first level of pertinence). This is the generation of build *forms* in concrete, which involves a *material*: concrete and a *technique*: casting. In-situ, or cast as elements, in which case the technique also includes assembly. In either case, the making of the *mould is a* subset to the technique, which for its own part involves a mould which has a *form,* and is made from a *material*, subjected to a *technique* (the second level of pertinence) (figure 6).

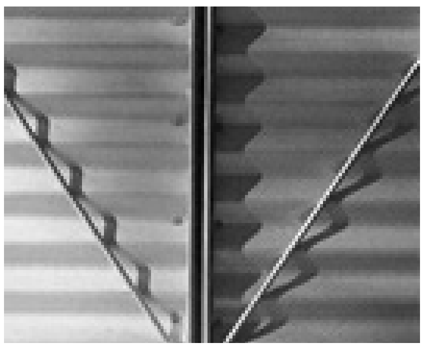

Figure 5: Simpson Lee House: Detail

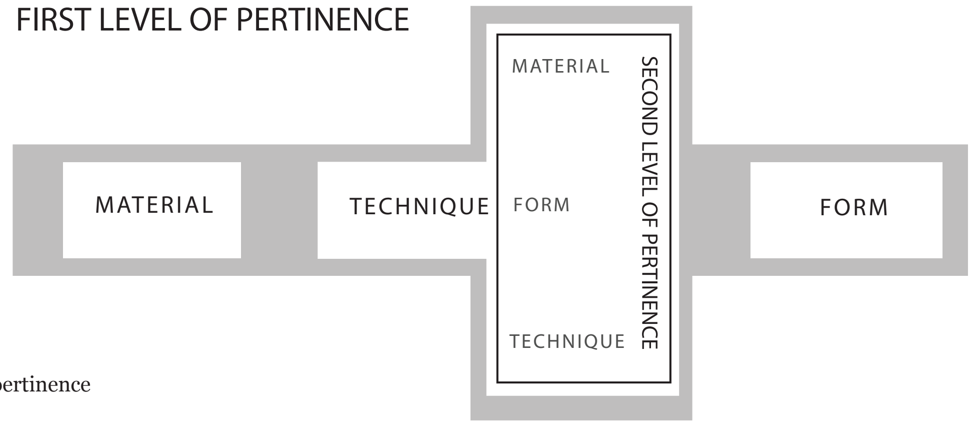

Figure 6: The two levels of pertinence

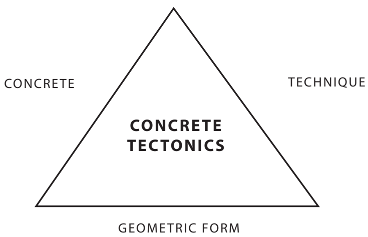

Figure 7: Concrete tectonics

CONCRETE CASTING RELATIONS

The first level of pertinence can be described as relations between material, technique, and form (figure 7). This understanding of making build forms in concrete is hence referred to as *concrete tectonics*. The three elements of concrete tectonics may be expressed like this:

- Material refers to the concrete itself, that is: stone, sand, aggregates, water, additives and possibly reinforcement.
- Technique refers to the casting process and the assembly process - the action of making the mould, casting the concrete, and post-processing the cured concrete into a construction (post-tensioning, assembly, etc.).
- Form refers to the geometric form of the cast concrete.

MOULD MAKING RELATIONS

The second level of pertinence is referred to as *mould tectonics*, because the *mould itself* may be viewed as a relation between material, technique, and form. Here, the three elements are expressed like this:

- Material equals the mould material.

- Technique refers to the making of the mould. That is, the addition, subtraction, or deformation of materials which creates a negative volume in which to pour the concrete.

- Form refers to geometric form of the mould.

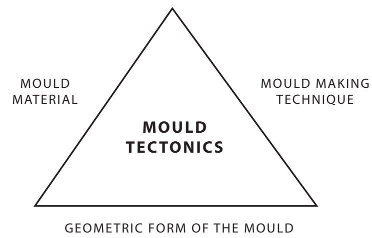

Figure 8: Mould tectonics

While the aim of the research is to discuss in depth the making of architectural forms in concrete and thus the understanding of *concrete tectonics*, the investigations and experiments will be focused on *mould tectonics*, since the forms in concrete relies on the form of the mould in which it is cast (figure 8).

RELATIONS BETWEEN MOULD AND CONCRETE

The form of the mould is a complicated matter because it is also a part of the concrete casting technique and the *form of the mould* should be evaluated as part of the *technique* of concrete tectonics as well.

Based on the here presented assessment of tectonics, and an empirical study of existing casting techniques (chapters four, five, and six), six case studies are carried out to examine specific material-technique-form relation regarding the creation of the mould, understood in the context of concrete tectonics (in chapters seven to eleven). In order to do so, some are dealing with isolated matters around the design of casting moulds, while others are dealing with aspects of architecture and aesthetics.

The analysis of the tectonic potentials of concrete is presented in chapter thirteen. The analysis constitutes a synthesis of mould tectonics with concrete tectonics (figure 9) on the basis of the empirical and case studies.

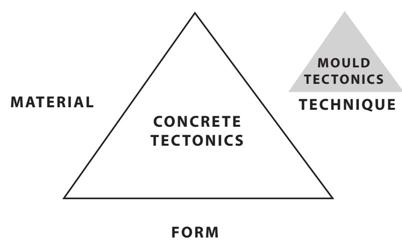

Figure 9: Concrete tectonics with emphasis on mould tectonics

CHAPTER 3: THE ART OF MAKING IN THE 21TH CENTURY

In the article 'Industrialiseret Individualitet' (Industrialised individuality) [1], Danish Professor Karl Christiansen and Associalte Professor Anders Gammelgaard describe a shift from standardisation to individualisation. Before industrialisation, they argue, craftsmanship was the framework for making. This way of working pointed towards unique forms, because the absence of automation made repetition irrelevant: the craftsman was proficient enough to perform this trade with variations without any deterioration in quality. After the introduction of factories and machines, repetitions became a necessity, resulting in mass-production. Making in the 21st century is still performed in the framework of industrialisation, but the advancement of computing, machinery and digitized control allow for the unique, or individual, to enter again.

According to the book 'Refabricating Architecture' by Matthew Kieran and Dominic Timberlake[2], the circumstances for architecture during the same period have changed dramatically. Architecture before the Industrial Revolution or industrialisation consisted of few materials and construction principles. The Gothic cathedrals, for instance, were erected by master builders, who had the roles of architect, process engineer and mason. A contemporary build-

1 Karl Christiansen and Anders Gammelgaard Nielsen, 'Industrialiseret Individualitet', Arkitekten, 2006, 55–59.

2 Stephen Kieran and James Timberlake, *Refabricating Architecture* (McGraw Hill Professional, 2004), pp. 26–27.

ing consists of a series of sub-structures of systems, the making of which are divided into segregated specialities, a circumstance that makes it impossible to return to this type of architect. On top of this, they argue, the complexity in regulatory demands is immense and new materials and construction principles develop rapidly. This fragmentation often leads to mediocre architecture because the initial concept, as conceived by the architect, is not aligned with the actual ways of making and is blurred in the realisation process.

In this perspective, the circumstances and possibilities in the art of making in the 21st century should take precedence in order to investigate how coherence between the architectural idea and finished building may be reintroduced. Given the advancements described above, an introduction to the concepts of *'New Production Philosophy'*, *'Mass-customization,* and *Digital Tectonics* is proposed.

NEW PRODUCTION PHILOSOPHY

The New Production Philosophy is an approach to manufacturing. In a rapport 'Application of the New Production Philosophy to Construction' by Finnish Professor Lauri Koskela studies the implications of this approach in construction. The rapport proposes a departure from a traditional view on construction. Traditionally, it is argued, construction was seen as the production of value, consisting of *conversion* from materials to constructions; inputs that generate an output. The benchmark for such production was productivity, understood as the ratio of input to output[3]. The rapport criticises the lack of attention to *flow* in the production process, which for its own part presents a significant use of resources and waste generation. Flow is understood as three processes: the design process, material process and work process. These activities should be described and optimised, something that the car industry has done efficiently and which require a process where construction is developed

3 Lauri Koskela, *Application of the New Production Philosophy to Construction* (Stanford University, 1992), p. 12.

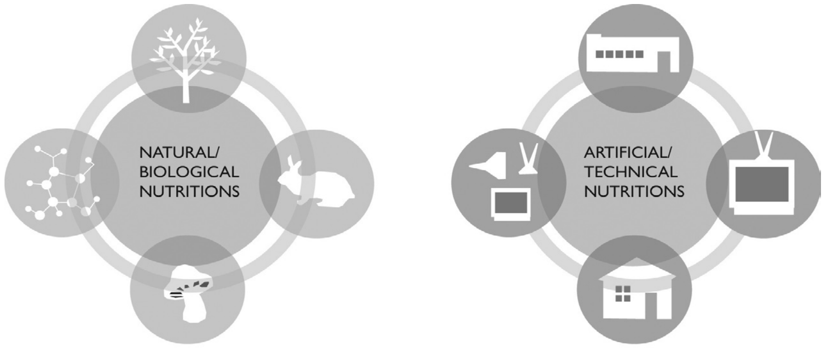

Figure 1: The two cycles of Cradle To Cradle: natural and artificial.

in conjunction with the design, not as a post-rationalisation[4].

Inspired by other modes of production, four approaches with relevance to concrete construction in architecture are identified: minimising waste, concurrent engineering, modules not parts[5] and modelling as opposed to representation.

MINIMISING WASTE

The process of making is itself important in reducing the use of resources[6]. Resources may refer to excessive use of raw materials or materials that are not recycled, but in the New Production Philosophy, to the use of other resources such as labour, energy, making errors, a poorly performing output and time are also considered. In this context it is relevant to consider minimising *material waste*. This can be done by viewing materials as either recyclable or biodegradable, a notion that is developed in the Cradle to Cradle strategy (CTC), in which materials avoid being reduced to mere means to an end. A material is never to be seen as waste, but always as a resource. Materials are divided into two categories: natural/biological and artificial/technical nutrients. The natural nutrients are viewed as part of a cycle. They are never waste, but become a part of nature after use (thus cradle to cradle rather than cradle to

4 Koskela, op.cit. rapport summary

5 Koskela, op.cit. pp. 7-8

6 Waste minimisation is a cornerstone in concept of Just In Time production, a part of the New Production Philosophy

grave). The popular idiom is “waste equals food”. The artificial materials are basically the materials that nature cannot break down and utilize as nutrition. These materials should be used with care in a closed cycle of use and re-use, in a way that does not downgrade the material (figure 1).[7] Poor performance of the output, in the case of concrete construction, could be read as failure to utilise the structural properties of the material to reduce the amount of concrete needed.

But there are pitfalls. In the book *the Conundrum* the American journalist and writer David Owen[8] describes such optimisations in the production of cars. It included increased recyclability and more efficient engines that use less gasoline. Paradoxically, Owen concludes, this has made cars cheaper leading to more cars being sold. This mechanism is what he calls *the conundrum* and it presents a significant problem in the case of concrete. In 2050, cement production will amount to 5 billion tonnes, five times today’s production. If more material efficient concrete constructions do become a reality, it is essential that regulations ensure that the production rates do not soar because of excessive use.

CONCURRENT ENGINEERING

The rapport on the New Production Philosophy concludes that flows in design to construction processes are often tacit and harder to generalise than in other productions. Arguably, this is why the car or aircraft industry often serve as a role model for discussing potentials in describing flows.[9] The car industry has fascinated architects since the early modernism and Le Corbusier famously stated that ‘the house is a machine for living in’[10]. Even so, construction is not directly comparable to the production of a car or an aircraft because of what the rapport calls *peculiarities*. Peculiarities describe the circumstance that architecture is one-of-a-kind projects, conducted by a temporary organisation of architect, client, contractor, regulations etc. The hypothesis of the

7 William McDonough and Michael Braungart, *Cradle to Cradle: Remaking the Way We Make Things* (Farrar, Straus and Giroux, 2010).
8 David Owen, *The Conundrum* (Penguin Group US, 2012).
9 Kieran and Timberlake, op.cit. p. 17
10 Le Corbusier, *Toward An Architecture* (Getty Publications, 2007), p. 87.

New Production Philosophy is, however the same as the one Le Corbusier promoted: that lessons may still be drawn from them.

Peculiarities are always present, especially in the work process, the act of building or assembling. But in the design and material process the New Production Philosophy may be used to emphasize problematic use of resources, the optimisation of which may be achieved if tectonic relations are addressed. This optimisation could address: overproduction, product design detached from material logics, too much machining (over processing) and avoiding defective parts or elements.

In conclusion, concurrent engineering is the inclusion of the constraints of production processes into the conceptual design and vice-versa. Design should be viewed as an iterative process, with a large number of iterations, between form-generation and production, where both factors are allowed to influence each other. This is opposed to a traditional process of generating form which is then adapted to a production in a sequential process. Kieran and Timberlake stress the necessity of strong relations between professions that architects seem to have avoided; contractors, product engineers, and material scientists.[11] Furthermore, they argue that a re-configuration of production processes and tasks with the aid of computing and automated fabrication equipment is needed. An example of such a setup is presented by the Australian computer scientist Rodney Brooks[12], who uses low-cost robotics to illustrate how locally based manufacturing may help re-introducing local manufacturing in the USA. One can conclude that the true potential of concurrent engineering lies within a coupling with local production facilities, in such a way that the design of the part is made under consideration of how the part may be manufactured at general purpose facilities as opposed to out-sourced and specialized production lines..

11 Kieran and James Timberlake, *op.cit*, pp. 49–52.

12 Rodney Brooks is a former professor of Robotics at MIT. His view on locally base manufacturing is presented at at talk on October 12, 2012 entitled ‘A new class of industrial robot’ at the The Robotics Institute at Carnegie Mellon University. A transmission of the talk is available on YouTube: http://youtu.be/RDvgNB2OZxI

CHUNKS

Kieran and Timberlake propose a re-configuration of architectural construction in order to take on the concepts of assembly found in aircraft or ship manufacturing. The aircraft or ship is assembled from very few sub-assemblies called *modules* or *chunks*, rather than the application of parts to create a whole. The chunks are large composites assembled off-site with their own structural integrity. The idea is that these sub-parts enable a break down that re-introduces the ability to overlook the overall idea of the design, while allowing self-contained units to design and produce the features of each chunk.

Diversity is hence achieved by means of permutations of the elements, not as the creation of entirely novel parts (figure 2). The tectonic potentials in this approach, they argue, lie in a possible dismissing of the idiosyncratic view of architecture as an image of something else, that is, an abstract formal or spatial concept which is then given materiality and physical appearance.

Examples such as the Montral Prefab Pixel City (figure 2) utilise a modularity in which variation is achieved by placing a limited number of types in a repetitive fashion, but various constellations. This is arguably not mass-customization but rather *montage*, a strategy which also offer significant variations, potentially leading to a higher architectural quality. This topic is unfolded by Danish Associate Professor Charlotte Bundgaard in the book 'Montagepositioner - En Undersøgelse Af Montagebegrebet i Industrialiseret Arkitektur'[13] (Montagepositions – an investigation of the concept of Montage in industrialized architecture). Bundgaard an investigates the concept of *Montage* in industrialized architecture as a strategy which offer significant variations, potentially leading to a higher architectural quality.

Figure 2: Montreal prefab pixel city: Module architecture taken to its extreme.

13 Bundgaard, Charlotte, 'Montagepositioner - En Undersøgelse Af Montagebegrebet i Industrialiseret Arkitektur' (Arkitektskolen Aarhus, 2006)

Kieran and Timberlake propose that the successful transition to this modular way of designing would include aesthetics that *arise* from the logics in the making, to become poetic by virtue of its ability to adapt to preconditions in manufacturing[14]. The aesthetic qualities would be similar to the ones found in vernacular architecture, in that it is tied to a reading of the buildings ability to make use of and take shape as a result of the efficiency driven mechanisms of optimising the manufacturing processes[15].

MASS-CUSTOMIZATION

Another concept within the New Production Philospohy is Mass-customization (MC). The concept (MC) is developed in the product industry, where manufacturing of computers and clothes among other goods are tailored to the customer's needs. The question can be raised if this kind of 'tailormade' applies to architecture, and present itself as a way to return to the inherent customisation found in pre-industrial handicrafts. Before discussing the current indications as to whether MC may or may not be able to provide for a similar diversity, a short introduction to the main concepts of MC is given. While the New Production Philosophy may be part of a mass-customized production, it is not a precondition. In the book 'Arkitektur & Mass-customization' (Architecture and Mass-customization)[16], the Danish Associate Professor Thomas Ryborg Jørgensen gives an account of mass-customization in an architectural context. In the book three distinct topics associated with a production which is mass customised are identifiey: The *differentiation level*, the *relationship level*, and the *solution space*.[17]

Differentiation level refers to an alignment between possible variations and the customer's need. Put differently, differentiation is made where it generates value, that is, gets an added quality. In an architectural context, this quality

14 Kieran and Timberlake, op.cit. p.109

15 Kieran and Timberlake, op.cit. p. 26

16 A fourth topic: The *cost level* is found less relevant in this context. It refers a use of mass-customisation which stays within a cost limit for the specific segment addressed.

17 Thomas Ryborg Jørgensen and CINARK (Institution), *Arkitektur & Mass Customization*, CINARK Overblik (København: Kunstakademiets arkitektskole, 2007), pp. 12-13.

could refer to the ability for architecture to enter a dialogue with the context, programmatic relations, or –in a tectonic perspective, a dialogue between the form and its origin.[18]

Relationship level refers to the gathering of information about the users of a given design, which over time provides a platform for new design and development, and even a change in behaviour of the same users. In an architectural context the topic becomes complicated, as buildings do not relate to a single user, but often a multitude of users. This points towards an understanding of the relationship level as related to user involvement.[19]

Solution space is perhaps the most interesting one in a tectonic context, as it addresses the actual production, as opposed the user. The main consideration addressed is how a stable production may be established which allows for flexibility. This is also called configuration, and relates to a special branch of digital form-generation: Parametric design.[20]

These topics address factors which need to be considered when mass-customization is applied in the product industry. Even though it is possible to recognize and understand the topics in an architectural context, the book questions whether they are always relevant. Similar to the idea of *peculiarities*, it is argued that the complex nature and foundational changes from project to project is a challenge because mass-customization is often applied only in the very last stage of manufacturing.
It may be argued that mass-customization has had some impact on the concrete elements industry, where the manufacturers offer individualised colouring of the concrete, aggregate mixtures, and surface treatments. Individualised surfaces have been achieved under the name 'Graphic Concrete'[21]. Using

18 Jørgensen, op.cit. pp. 22–25.
19 Jørgensen, op.cit. pp. 27–41.
20 Jørgensen, op.cit. pp. 43–53.
21 Graphic Concrete Ltd is a Finnish company using a patented technology invented by interior architect Samuli Naamanka.

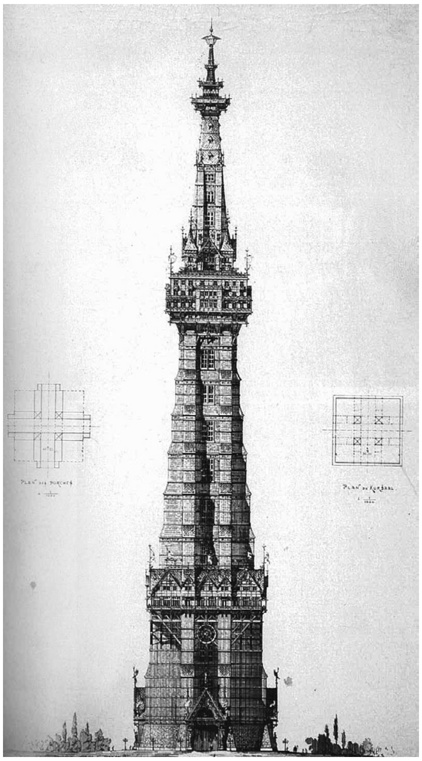

Figure 3: William West Neve: wooden tower on a concrete base

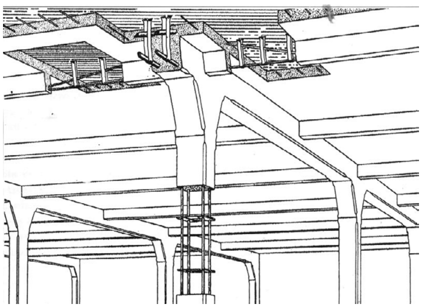

Figure 4: Francois Hennebique: drawing of concrete as a system

large scale printers, a retarder is printed on paper which is placed in the mould, allowing for individualized surface characteristics on each element. This 'cosmetic customization', however, has impact on material characteristics only, not the actual geometry of the concrete elements. As such it does not imply a ground-breaking shift from the existing repetitive concrete element production. In fact, no examples can be found where the concrete elements themselves are individualised.

According to Bundgaard, the montage-strategies may represent an approach which is able to embrace mass-customization. But the question about what true individualisation means for architecture, remains unanswered.[22]

DIGITAL DESIGN TO PRODUCTION

Kieran and Timberlake argue that the increase in complexity which follows new fabrication processes requires a shift in representational means. Instead of using representation as a proxy (a stand-in for the original), they suggest digital modelling and *simulation* as a mode of representation not limited to a particular fixed point of view, both geometry and manufacturing processes at the same time.[23]

While simulation and digital modelling does appear promising in this regard, there is a long tradition of representing buildings in concrete, which should not be neglected. The following account of the development in the ways concrete has been represented is put forward to put representation as simulation into perspective.

CONCRETE REPRESENTATIONS

In the representations made before the industrialisation, architects did not depict the material concrete itself, neither the process of the making, nor the characteristic physical properties of the material. Instead, con-

22 Charlotte Bundgaard, 'Montagepositioner - En Undersøgelse Af Montagebegrebet i Industrialiseret Arkitektur' (Arkitektskolen Aarhus, 2006), p. 148.

23 Kieran and Timberlake, *Refabricating ARCHITECTURE*, p. 59.

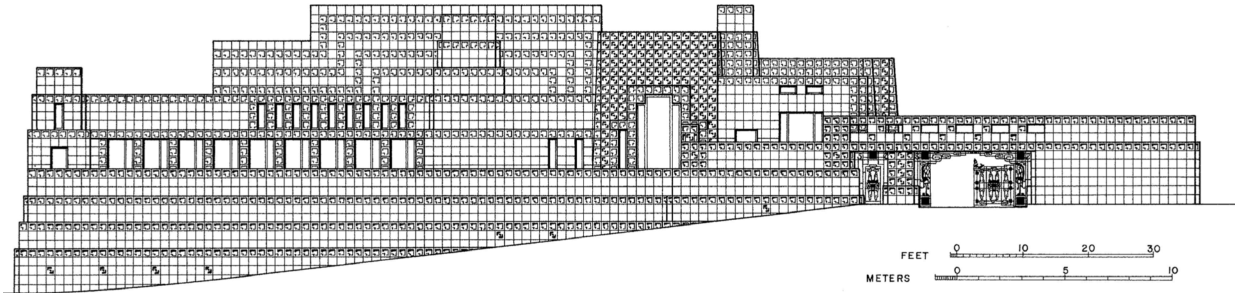

Figure 5. Frank Lloyd Wright: The Ennis House in Pasadena

crete was represented in the same way as stone: that is as an addition of building blocks, as in the drawing of a wooden tower on a concrete base (figure 3).

The nature of representations changes in the 20th century. The drawings of Francois Hennebique show concrete as a system rather than a mimesis of another material. Hennebique illustrates how columns and beams are melted together into a monolithic structure, thus depicting the in-situ casting process and the composite properties of concrete (figure 4).

In 1924, Frank Lloyd Wright drew the Ennis House with a facade of texture of blocks with a repeated pattern. This drawing also tells something about the process of concrete. Again concrete is represented as a system – this time a system of elements with a complexity, durability and preciseness to them that makes is hard to think of the façade as being anything but concrete elements, all alike and cast in the same form (figures 5 and 6).

The two last examples illustrate different representational strategies, both showing the plasticity of the material, adding a layer of information that is not present in earlier drawings where concrete is sketched to mimic stone blocks.

Figure 6: Frank Lloyd Wright: Ennis House, Pasadena. Façade

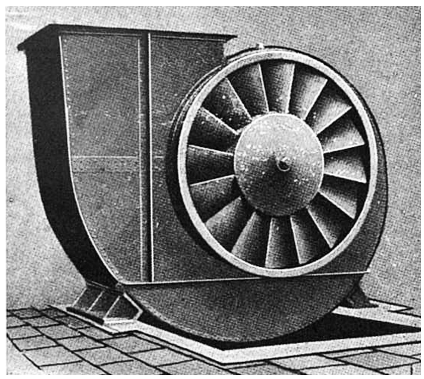

Figure 7: Le Corbusier: a mechanical object used to describe the modern project.

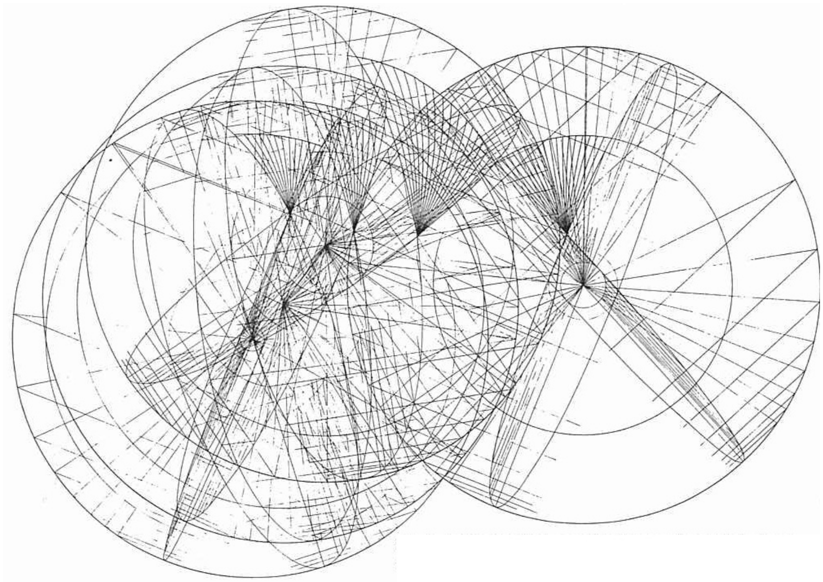

Figure 8: The geometry and division of the shells of the Sydney Opera House

Le Corbusier introduced an altogether different mode of representation, one that transcended the built object itself. Instead he used illustrations of the industrial logic that was the basis for the design to describe the concept of the building, as part of the modern project. The Spanish/American Professor in Architectural history Beatrice Columina has described the image of a Rateau ventilator as an example of this pun on the meanings of industrial revolution (figure 7).[24]

In the article ‘A New Materiality’[25] the American Professor in architecture history Antoine Picon argues that the use of mechanical objects as metaphors has the danger of being taken to literally, removing architecture from the realm of phenomena. A statement which is recognizes with the ‘truth’ put forward by Heidegger. The expressive modernists may be said to escape this reduction. Using abstract metaphors, rather than examples from the industry, the process or the technique to produce form was a visible and central part of the rep-

24 K. Michael Hays, *Architecture Theory Since 1968* (MIT Press, 2000), pp. 624–654.

25 Krista Sykes, *Constructing a New Agenda: Architechtural Theory 1993-2009* (Princeton Architectural Press, 2010), pp.270 - 287.

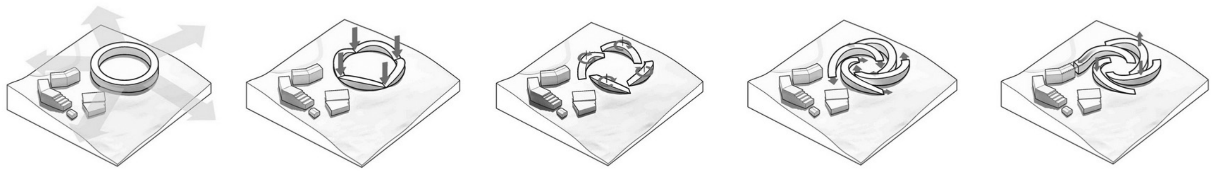

Figure 9: BIG architects: the formal conception of the Koutalaki Ski Village

resentations and the architecture[26]. Jorn Utzon's drawings of the shells of the Sydney Opera House are illustrative of this ideal in representation: The drawing of the geometrical logics of the shells look towards technology and the process to push the boundaries of mass production, but leaves it up to the viewer to determine whether to focus on the production principle or the architectural composition itself (Figure 8).

The representations made by Le Corbusier and the expressive modernists are both examples of how underlying thoughts and processes in the making of architecture are included in illustrating both the means and the end. It may be argued that this richness has been somewhat neglected and needs to be re-activated in order to utilize the potentials for architecture found in tectonics and new production processes.

While digital representational methods today enable the description of complex shapes and processes, they are seldom used to represent the process of making. Instead, a storyline rooted in formal or functional foci tells a story about arbitrary, non-existing steps that have been taken mentally to arrive at a form. Only then is the building evaluated and further developed into parts and a constructive system (figure 9). Architecture that originates from this line of thought naturally revolves around the foci represented in the storyline, which is often purely spatial. Tactility and material quality are *photoshopped*[27] in from reference images, rather than derived from the logics of the building itself (figure 10).

The idea of simulation is intriguing in that a simulation tells the story of

Figure 10: Cebra: Marina House, Aarhus. Texture and depth is given by reflections from the sky and an image of the city.

26 This assumption is elaborated in chapter 4: "Tectonics in the Sydney Opera House"

27 A term that covers the act of digitally enhancing images or sampling images from one scenario onto another.

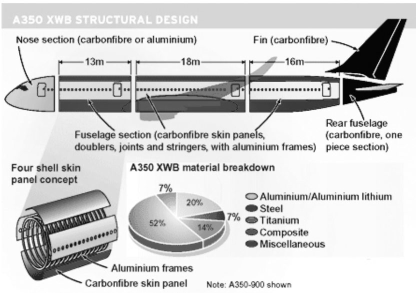

Figure 11: The airbus A350 shown as a number of blocks, and their assembly.

the *actual* making of the construction, rather than an arbitrary one, as seen in the car, aircraft and ship industries (figure 11), but they are not dealing with *aesthetic value* and the phenomenological nature of architecture, which the modernists were so successful in showing. So while simulation seems like a great tool for insisting that the processes and parts (hence materials and technique) is central, the method should be accompanied by traditional means of representations, such as drawing and physical modelling.

DIGITAL TECTONICS

The American Architect and Theorist Niel Leach has dubbed this broader understanding of digital modelling "Digital Tectonics". In a book with the same name[28] Leach suggest that the notion of digital tectonics foresees the disappearance of the dichotomy of the digital as opposed to the tectonic. With a particular interest in structure, the idea is that the computer should be used to drive a process which folds into representation, meaning that use of the computer in the *development* is prioritized over its use for *representational* purposes.[29] This requires a skillful use of the computer as an animator of fabrication equipment, in order to be able to use the computer and machine for making artifacts with aesthetic qualities. Such use is referred to as *machinic* as opposed to a *mechanical* use, which does not utilize aesthetic potentials inherent in the tools[30]

One such approach is the process of computing *formation* as opposed to form, as known in the analogue model photos of Frei Otto's hanging chain models (figure 12). In the process the element of time is a key factor in the actual form generation, while the factors driving the process are the ones defined by the architect, not the form itself. If conceived with the material and technological circumstances in mind, the result can be

28 Turnbull et. al, *Digital Tectonics* (John Wiley & Sons, 2004).

29 Turnbull et al, op.cit. pp. 4–12.

30 Gregg Lynn in conversation with Neil Leach: The structure of Ornament, *in Turnbul et. al, op.cit. pp.63-68*

said to become tectonic. In other words, the digital representation concerns dynamic relations between materials and forces over static ones of form and matter.[31] The potentials of this approach are that structural performance can be simulated and that production workflows can interact and form a basis for the representations, given a productive dialogue between architect and engineer.[32] A recently concluded research project 'Generative Algorithmic Techniques for Architectural Design' By Danish Architect, Lecturer Niels Martin Larsen describes these potentials for using generative strategies in architectural design.[33] In collaboration with the author a generative approach to modeling of concrete tectonics is investigated.

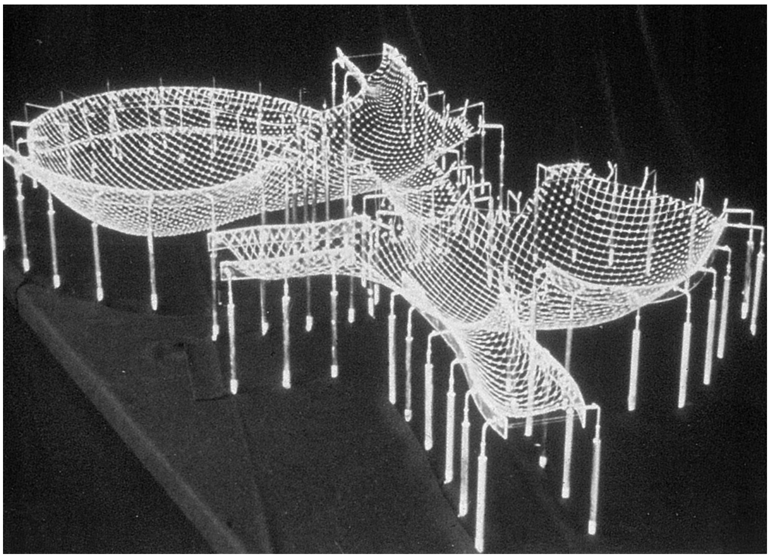

Figure 12: Frei Otto: model studies of the Multihalle Mannheim

31 Turnbull, op.cit. pp. 74-75
32 Chris Williams: *Design by algorithm in* Turnbull, op.cit. pp. 78-88.
33 Niels Martin Larsen, *Generative Algorithmic Techniques for Architectural Design* (Aarhus School of Architecture, 2012).

PART II
EMPIRICAL STUDIES

CHAPTER 4: TECTONICS IN THE SYDNEY OPERA HOUSE

Figure 1: The Sydney Opera House. Concrete shells on a concrete base.

It is relevant to look at one of the highlights of tectonic architecture in which the form is the result of utilizing concrete casting in the era of mass production: The Sydney Opera House by Jorn Utzon (figure 1). A canonic piece of architecture, an account of the use of concrete and the tectonic relations found herein can be used to measure other cases against for three reasons. First the architect had the intention of building it from concrete from the start. Second, the process of developing the initial sketches into the finalized construction was centered on the casting and construction of the concrete elements that make up the primary

construction of the opera house. Third, the project marks an important era of the modern movement, which is built on ideas of industrialism and mass production of standard components. [1]

One of the main preconditions of the Sydney Opera House is its location on a peninsula in the Sydney Harbour Bay, unusual because of its exposure from all sides. The site effectively has no back side, not even from the fifth facade, where a declining terrain from the Central Business District towards the bay gives a view of the site from above. The nearby skyscrapers enhance the situation. An elongated park stretches across

1 Karl Christiansen and Anders Gammelgaard Nielsen, 'Industrialiseret Individualitet', Arkitekten, 2006, 55–59.

this sloping terrain from the city center towards the bay. The Sydney Opera House is situated at the end of this stretch, presenting itself as an extension of the public floor space of the city.

Conceptually, it consists of three elements: the base, which takes on and extends the public floor; the auditoriums which serve the opera function; and the shells which respond to the exposure and thus the three-dimensionality of the site. It is primarily the shells that are the focus of this analysis.

The development process of the concrete shells is central to understanding the tectonic aspects of the project. The initial idea was to create an elevated plateau, on which the opera activities could take place and cover them with thin concrete shells (figure 2).

The competition brief stated that the shells were to be constructed in a manner similar to the ones Eero Saarinen planned for his proposal for a new TWA terminal at JFK airport in New York, the construction of which started in 1957, one year prior to the beginning of the design of the Sydney Opera House[2].

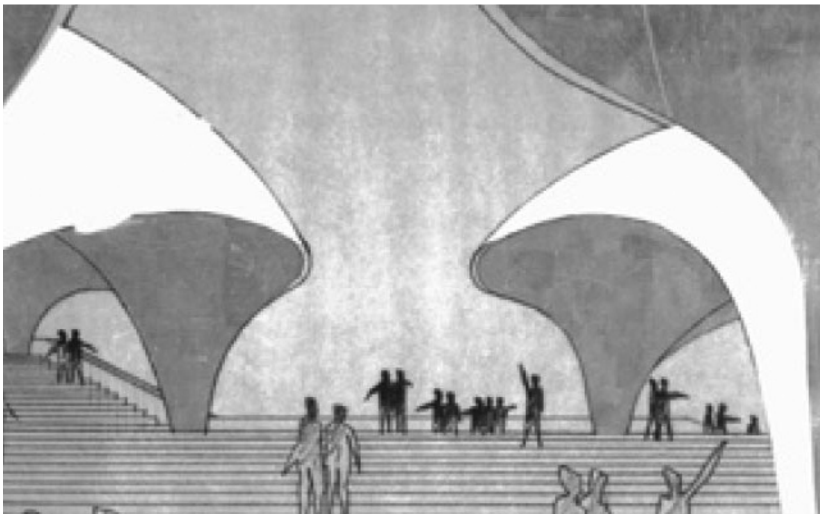

Figure 2: Perspective from the competition entry showing thin, in-situ cast concrete shells

2 Yuzo Mikami, 'Utzon's Sphere : Sydney Opera House : How It Was Designed and Built' (Shokokuska, 2001)

THE SHELLS

The development of the shells illustrates relationship between technology, construction and cladding which gives rise to a claim that the shells represent a complex relationship and a duality between the construction and the cladding, in which there is a tectonic *coherence*. The architectural theorist Rem Koolhaas has used the word coherence to describe striving to arrive at an ideal form, in opposition to multiplicity, which describes flexible architecture[3].

Tectonic coherence is used here to describe the circumstance that the form points towards the construction, but also the other way round: that the construction points towards the form. It follows that the construction is coherent with its premises, these being the technological situation and the overall concept of the opera house design. In other words, there is a dependency between form, matter, and technique.

In the early design phases after the competition was won, it was found impossible to make use of ultra-thin concrete shells, due to the large spans required.[4] This fact led to the long collaboration with the engineer Ove Arup, of which the realized construction of the shells is the result (figure 3). It is from this process that the tectonic relations between material, technology and form arose.

During this process, a principle was developed which would both allow for the large spans required and fit into an industrial logic of mass-production of standard elements. The well-known history of the adoption of the shells into a spherical geometry was necessary in order to be able to further divide each shell into ribs that were capable of dealing with compressive and torsion-forces. These ribs were then subdivided into up to 13 standard elements, depending on the size of the shell (figure 4), elements which were light enough to be lifted into place by a crane and post-tensioned to become stable in compression. This post-tensioning is evident in the large details at the base of the

3 Rem Koolhaas and others, S, M, L, XL (Crown Publishing Group, 1998).

4 Richard Weston, Utzon: Inspiration, Vision, Architecture (Edition Blondal, 2002).

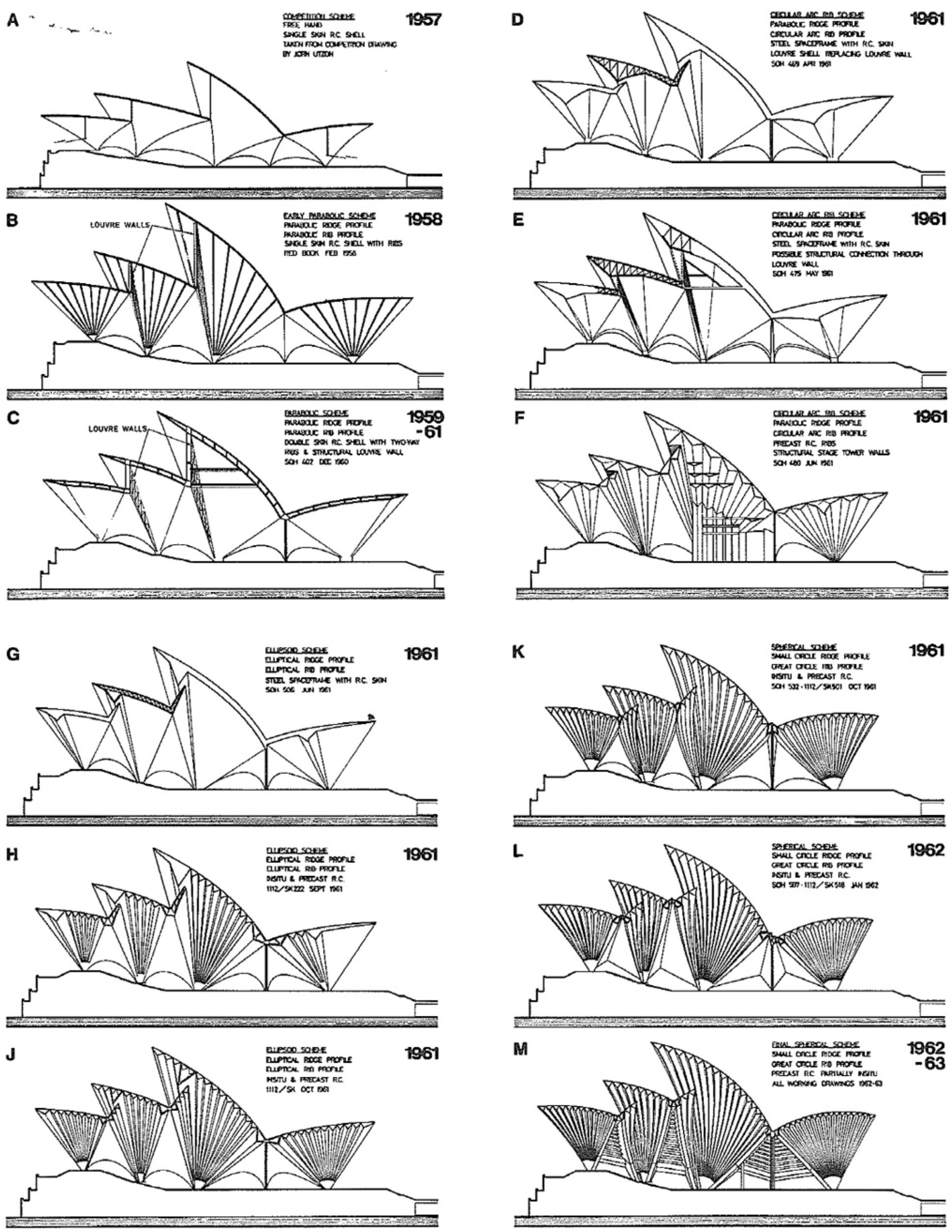

Figure 3: The development of the roof design from 1957 to 1963

shells (figure 5).

This definition by means of Euclidian geometry does not ruin the three-dimensionality of the shells; one may even argue that the feeling of being in a non-rectilinear space is enhanced because the eye finds reference in the spherical geometry. Hence, the concept of the expressive elements on top of a calm base points towards the form of the shells, just like the technology does. And the form for its own part points back at the two.

Utzon wanted to clad the shells in ceramic tiles. The idea was to break down the vast scale of the shells into a pattern of a size perceivable by humans, creating a visual hierarchy. Further, the shine of the ceramic tiles would have given the shells a vivid interplay with the sky and lighting conditions. But it was not possible to panelize the cladding into a rectilinear grid due to the trapezoid shape of each concrete element. This circumstance was dealt with by finishing off each row with one of 17 special tiles which get progressively narrower, until the overall width is so small that the widest tile can be used again. This strategy is exactly the same as in the concrete element construction itself. The tiles point to the main construction, which in turn points back to the tiles (figure 6).

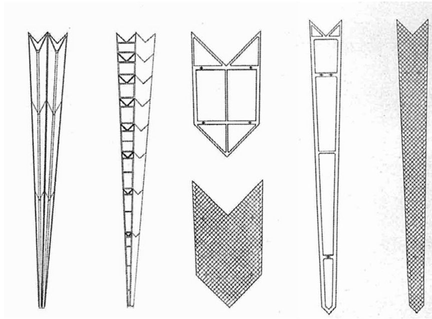

Figure 4: Each rib is made up of a limited number of different concrete elements.

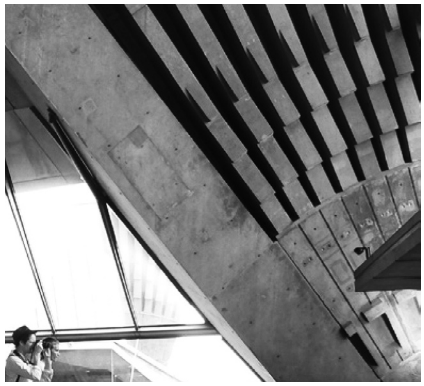

Figure 5: The detail tells about the process of post-tensioning cables within the ribs.

Figure 6: Repeated use of 17 diffent tiles solves the edge condition of each rib element.

PARADOXES IN THE SHELLS

The above mentioned relations result in the shells encompassing so many aspects which define and refer to each other and create a circumstance where it is not possible to perceive all aspects at the same time. A paradox arises, similar to the one existing with the Giant's pot, as the term 'the shells' is a placeholder for a complex constellation with many facets. This paradox arises as the parts begin to refer to each other, to become a closed whole. It is possible to focus on the coherence between the ribs and the cladding, or between the concept and the construction, but not both at the same time.

The characteristic appearance of repetition that is often visible in buildings made from concrete elements is absent in the shells of the Sydney Opera House. Like (with) the spherical geometry, the visual impact of the modularization becomes stronger because the eye finds a resting point in the familiarity between elements.

THE MEETING BETWEEN RIBS AND BASE

There are ten shells in the Sydney Opera House. Six of them rest on two of the aforementioned consoles, in which the tension wires meet, forming an independent structure. The remaining four shells are connected. One of the fundamental principles of statics is that a construction needs to touch the ground in three places in order to become stable, unless it is fixed, which the six independent shells are not. Therefore the shells are erected against large A-shaped concrete trestles, against which they are post tensioned (figure 7).

As these trestles also cope with torsion forces, the remaining forces in the con-

Figure 7: The shells rest against large A-shaped frames, made up of concrete elements.

soles are compressive and sliding forces. The sliding forces are handled by tension cables cast into the base. It follows that the forces are meeting at exactly one point – which is not shown. Here an opening between form and construction exists. As previously mentioned, the gathering of forces from the ribs into the in-situ cast console is clearly visible. It is the subsequent flow of forces as well as the tension cable which are unarticulated. A more articulated option would be to make a ball- joint. This is not possible, but a change of material into metal in the bottom part of the console could be done. Or, the point could be nothing, a point in space with the forces and material flowing around it, as we see in the works of Carlo Scarpa.

Figure 8: The load bearing , in-situ cast walls are visible through open joints

PROBLEMS IN THE BASE

The closed relation found between the construction and the cladding in the shells is not present in the base. A consistent principle of whether the construction is visible or hidden is lacking; three different situations are found.

Figure 9: A fully exposed load bearing construction

There are places where the construction is hidden but open joints between the concrete element cladding (tells about) reveal the in-situ cast concrete walls beneath, as for instance in exterior and interior walls (figure 8).

Then there are places where the in-situ cast construction is shown with no cladding, as for instance inside and around the concourse beam (figure 9). Finally there are places where the construction is hidden entirely, as on the steps over the concourse (figure 10). The different principles make it hard to create a consistent mental image of both the constructive

Figure 10: The load bearing construction hidden beneath the cladding

principle and the tectonic relations between cladding and construction.

THE CONCOURSE BEAM

Closed tectonic relations are present again around the concourse beams: here, the relation is particularly evident around *form* and *matter*. It is the case, where the construction is exposed; creating an easily readable relationship between the monolithic, in-situ cast load-bearing concrete and the smaller non-structural, precast concrete element cladding. Further emphasizing this distinction is the shape of the concourse beams. They are optimized structurally to match the forces at a given location and post-stressed to counteract downwards deflection across the span (figure 11). This reduces the weight of the beams. Interestingly, the properties and formal potentials of the mould material are evident in the geometry of the concourse beams. They are cast in long plywood moulds, allowing a twist in one direction and linearity in the other. The function of the concourse beam, to cover a long span and to carry the cladding panels, is evident through the form.

CONCLUSION

In conclusion, significant parts of the Sydney Opera House, that is the shells and parts of the base, are a testimony to of a very strong coherence. At the same time the analysis indicates that architecture of this scale and complexity can always be criticized. It can be argued whether the fully tectonic piece of architecture is at all possible, or even desirable.

As mentioned, Rem Koolhaas used coherence to describe architecture which strives towards ideal form. Favoring a flexible architecture of multiplicity, he criticized this type of architecture for being either cosmetic or the result of a deceiving self-censorship.

The claim here is that the coherence found in the Sydney Opera House is not

Figure 11: The structurally optimized form of the in-situ cast concourse beams.

purely cosmetic, because the choices made in the making and construction refer back to the concept, which for its own part, points towards the visitor's subjective judgment of the architecture, rather than the ideal form, towards which Mies Van der Rohe was striving. Whether it is sails in the wind, rolling waves, turtles having intercourse or something else.

The Sydney Opera House has both multiplicity and coherence, or perhaps better; *complexity*.

It is 'itself' and does not try to be anything else, which is probably why visitors try to apply symbolic value to it by addressing it with nicknames. There are endless ways of interpreting it and it is up to the individual to form his or her own opinion, as is the case with other art forms. That this House is world-class is not only because of this feature, but also because of the stories found in the visible and understandable relationship between concept, form, material and construction.

CHAPTER 5: CONCRETE CASTING IN ARCHITECTURE

The success and durability of a concrete construction is determined by the mixing and subsequent moulding of a liquid mix of cement and aggregates before it cures. To execute these necessary steps, architects and engineers can draw upon a range of well-proven or experimental casting principles. In chapter two, *Concrete tectonics* was defined as the relationship between concrete, the mould and the geometric form of the cured concrete. *Concrete casting* is the action performed to create the geometric form: the actual pouring of concrete into a mould. This can be done in two ways: on the site or in a factory. The process of *in-situ casting* or *elements casting* poses a series of limitations and possibilities, respectively. An assessment of the pros and cons of the two modes of casting concrete is necessary, as it influences the properties of the mould.

The material contents and properties of concrete also affect the geometric form. It is, however, outside the scope of the research to present a thorough account of this topic. It would include the possible ingredients, the different ways of mixing it and considerations necessary to ensure the curing process is successful. An introduction to this field can be found in the book 'Constructing Architecture' by German Professor Architect Andreas Deplazes[1]. But an important observation is that liquid concrete is isotropic. That is, without will to take on a specific shape, apart from that dictated by gravity and the viscosity of the liquid, which makes the formwork the sole guiding force for dictating shape. Yet the weight and viscosity cannot be neglected. Concrete is heavy.

1 Andrea Deplazes, Constructing Architecture: Materials, Processes, Structures, a Handbook (Springer, 2005) pp.60-62.

IN-SITU CASTING – PROS AND CONS

The process of casting concrete in-situ is labour intensive. Since the casting has to be done in place, it is not possible to cast the building parts horizontally, and casting vertically results in great stress on the formwork from the heavy, liquid concrete. Therefore, custom built complex support systems have to be constructed in order to prevent the mould from buckling or breaking. Site restrictions and weather conditions further complicate matters.

These factors make it important to plan ahead and control the building process. Correcting mistakes is difficult or impossible post-casting and quality control further increases the labour intensity. Put differently, a high level of expertise is required to benefit from the advantages of casting on site. So, what are these advantages, and what makes in-situ casting an attractive alternative to element casting?

First of all, in-situ cast concrete is monolithic (figure 1)[2], because the concrete is cast on site with no limitations in the size of the castings. From a constructive point of view, this has the advantage that compressive, tensile, and shear forces are running uninterrupted in large areas. This advantage is utilised in projects like dams, bridges and water towers where one giant mould is constructed and filled in a running process. Adding to the constructive potentials are the possibility for post-stressing or post-tensioning, which enhances the in-situ cast concrete's resistance to deflections, as seen in the concourse beam of the Sydney Opera House.

In other words, the architectural potentials of in-situ cast concrete lies in the heaviness and three-dimensionality, which are influenced by the materials plasticity and strength (figure 2). Also, in-situ cast concrete tells a story of permanence: Once completed, any errors or imprecisions in the casting are impossible to correct. Whether that is an advantage or drawback depends on the observer's position; it may provoke feelings of intrusiveness and hostility,

2 Deplazes, op.cit. p 57


Figure 1: Louis Kahn: Salk institute


Figure 2: In-situ cast concrete in a butcher's house in China.

or solidity and calm.

The appearance of the concrete is dependent on the materials used in the mix and nature of the mould. In-situ cast concrete in which local sand and stone is used makes the concrete blend into the surroundings (figure 3). The mould material is visible in the finished concrete casting: rough wooden boards give an equally rough concrete surface with a relief depicting the structure of the wood. Steel, plywood covered with resin, or similar plate materials give the concrete surface a smooth appearance with a dynamic shine.

Each project can be seen as a prototype, because the primary reason for opting for in-situ casting is the ability to give the architecture complex,

Figure 3: Frank Lloyd Wright: Taliesin West. Crude in-situ cast concrete walls with large, local stones and local sand used

monolithic shapes and a unique character. Architecture that is composed of basic or modular geometries points towards the use of concrete elements instead of in-situ cast concrete. As noted by Deplazes[3], the lack of standards means that formwork and reinforcement is usually custom-made and that the construction of the formwork is complicated. The casting is naturally vertical – which creates a massive hydrostatic pressure on the mould. It follows that a robust, resource intensive formwork construction is needed. In effect the construction is built three times: as a mould; and then, in a somewhat abstract manner, as the reinforcement; and finally in concrete. Commonly the concrete needs to be insulated, in which case a fourth and fifth iteration is

3 Deplazes, op.cit. p. 63

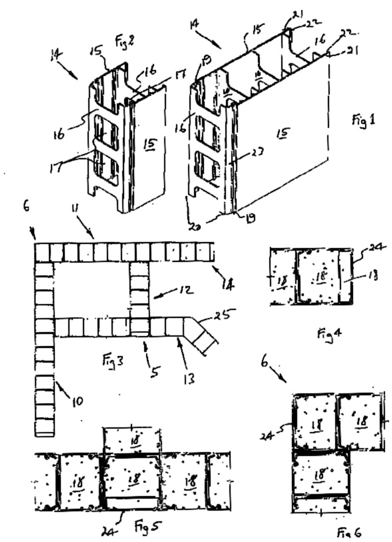

Figure 4: The Dincel ® Construction System: concrete cast in PVC elements.

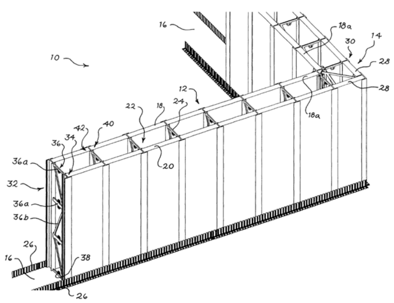

Figure 5: Insulated Concrete Forms

required, namely the addition of additional formwork and casting to cover internal insulation.

Further, the task of laying out the reinforcement often takes place inside existing formwork which makes it hard to work with. The construction of the formwork and casting is subject to weather conditions, which require a high skill level to handle. A concept called *System moulds*[4] seeks to deal with these issues by standardising the moulds into either reusable modules in light-weight materials such as aluminium, or building blocks that stay in place after the cast, serving as mould and surface (figure 4). Systems entitled *Insulated Concrete Forms*[5] offer blocks that function as moulds and contain insulation (figure 5). Systems moulds, however, restrict the geometry, which is counter indicative to the fundamental architectural potentials of the in-situ casting technique described above. Insulated formwork is especially problematic with insulated concrete as the robust, weatherproof material is hidden beneath a fragile layer of insulation material.

PREFABRICATED CONCRETE ELEMENTS

Prefabricated concrete elements are concrete elements manufactured as separate elements which are assembled into a construction. The main difference from concrete cast in place is the limitation in size, defined by restrictions in the production facility and in transportation.

Prefabricated concrete elements avoid several of the issues associated with in-situ casting. Elements are cast in an indoor environment where the temperature and humidity can be kept constant and the precast concrete production line is not a temporary, one-off setup as it is the case when casting on site. Also, a rigorous quality control is possible, and errors are not as catastrophic as when casting in place, since the faulty

4 Several companies offer system formwork. See for instance Moladi's plastic formwork: http://moladi.com/plastic_formwork.htm (visited 22-04-2013)

5 As with regular system formwork, several products are available. For instance BASF's LOGIXTM ICF.

element can simply be re-done. Owing to the controlled environment and quality control, the surface quality of concrete elements is generally higher than that of the surface of concrete cast in place. When it comes to mass production where moulds are re-used, it is feasible to use materials of a high surface quality.


Figure 6: Two sandwich elements supporting each other while awaiting transport.

Precast fabrication allows for the use of advanced technology in an industrialized environment, offering the benefits of the New Industrial Philosophy, as described in chapter two. The industry is currently approaching a production of sub-assemblies or *chunks* rather than simple elements. The modular bath is an example of such a setup. It is produced as a self contained unit with walls, floor, roof, and installations added before delivery on site. This means that the ability to manufacture finished building parts including installation ducts, insulation, cladding, windows, etc does exist[6]. The *sandwich element* (figure 6), which is used extensively in today's building practice lies somewhere between element and chunk, as it consists of both the inner and outer wall with insulation between. It is, however, not a sub-assembly in terms of the new production philosophy, as it is not a statically determined, finished part of the building

These abilities to industrialize and control the production are the causes of the success of mass-produced concrete elements, despite the fact that the overall form needs to be broken down into elements (figure 7).

Notably, the advanced nature of the production line has addressed the fact that concrete elements do not have the same constructive properties as concrete cast in place. The re-enforcement is not connected between elements, disrupting the translation of shear and tensile forces. This is addressed by casting tiers into the elements, allowing them to interlock upon assembly. Furthermore, techniques for post-tensioning elements together have been developed, as seen with elements in the shells of the Sydney Opera House described in chapter four. Finally, an improvement

6 See for instance http://modulbad.dk/ (visited 22-04-2013)

Figure 7: Industrialized production of prestressed concrete floor elements on a large scale

unique to the production of elements is *prestressing,* which increases the elements' ability to span between supports. Prestressing is done by building the mould around tensioned steel cables, which become enclosed once the pour is complete.

Concrete elements, however advanced, cannot escape the fact that they must be *joined.* Attention is thus required with regard to tolerances, to stability, to the transferring of forces as mentioned above and to the aesthetic consequences of working with elements which are defined by size and joints. Owing to the bad reputation of concrete element buildings, as described in chapter one, a widely used strategy is to hide the joints. In a tectonic perspective this seems like an unacceptable solution: the concrete loses its purpose as an illustrator of its origin, as concluded in chapter two. For the story of the building as a puzzle-piece of interlocking elements to remain intact, the joint is importantas a minimal unit in the process of signification, as concluded by Marco Frascari[7]. It may be articulated by a change of material, by a change in geometry, by introducing a gap (figure 8), or by something different.

In conclusion, the precast principle seems more advanced and controllable in comparison with casting in-situ and thus the right choice of study for the case studies. On the other hand, precast concrete in its current form is used exclusively for the mass production of repetitive elements, which limits the potentials for creating complex geometries. With reference to the precast elements which make up the ribs in the shells of the Sydney Opera House, however, the question arises if it is possible to create *individualised* geometrical forms in precast concrete which have the three-dimensional qualities otherwise only found in labour-intensive and expensive concrete constructions, which have been cast in-situ.

7 Frascari, Marco, 'The Tell the Tale Detail', Via, 23–37, p. 12

Figure 8: Gantly Adams Airport: The meeting of the concrete roof beam and slabs are articulatated as a gaps.

CHAPTER 6: CASTING TECHNIQUES WITH TECTONIC IMPLICATIONS

Several recent projects have been set forth to investigate if it is possible to cast individualised concrete elements in complex shapes. While these are not limited to examining concrete element constructions, a majority of the projects put focus on concrete elements, for the reasons stated in the previous chapter. The following is an account of these projects focusing on the mould materials and casting technique used in the projects and the *tectonic implications* present. A central question in this regard is how the casting is, or may become individualised by means of computer controlled technology.

In this account of the state of the art, potentials and barriers in existing research are identified. As such, the examples mentioned here serve as a blueprint for building case studies and for analysing the findings of these case studies. The casting principles and mould materials here presented are not selected on the basis of whether they represent a well-proven casting principle widely used in practice. Also, the examples are not to be considered a design manual with methods of how to mix concrete or how to construct a mould. The aim is, as stated above, to highlight materials and techniques with tectonic potentials which may be part of an individualized, industrial production in order to be able to propose a number of casting techniques that will provide similar or enhanced features.

One can postulate that there are three ways of creating a mould are possible: addition, subtraction, and transformation (A-S-T). Each method represents a *method* or *operation* on a material with which to create a form. As such, the division focuses on the mould creation, with particular emphasis on the *technique* used to perform this operation on a *material*, transforming it into casting mould, as described in chapter two. In the practice of A-S-T, moulds are always constructed by means of adding, subtracting, or transforming (bending, deforming etc.) one or more materials, or a combination of two or even all three operations. The concept of A-S-T is fruitful in that it transcends the traditional distinction of in-situ cast concrete versus concrete elements, as described in chapter five. Instead, the *coherence* of means and result, which is central in tectonic thinking, is in focus. For instance, a material may have properties which point to one mode of operation, but not another. The same can be said for a technique. Furthermore, the modes of operations may have implications for geometric form: addition point towards Euclidian geometry, while subtraction point towards non euclidean geometry.

That is not to say that the distinction between in-situ versus elements of other dichotomies, such as cheap versus expensive, are not of importance. But in order to adhere to the hypothesis that tectonics is a starting point for the development of new methods, a distinction between addition, subtraction, and transformation is fruitful when analysing the advantages or problems of using certain materials and techniques. Thereafter it can be established if the method is suitable for casting in place, or elements, or if the mould-making is really a combination of more than one method.

STATE-OF-THE-ART: ADDITION

The concept of adding materials to form a mould is the classical idea of concrete casting and the most widely used. Moulds for casting concrete are constructed by adding pieces of material to create an enclosure for the liquid mass. The materials used are euclidean with just a few exemptions, presenting a geometric restriction to the inherent amorphous nature of concrete itself.

CONFAC

Confac Concrete in Randers, Denmark is a production which specialises in making concrete elements by means of adding pieces of mould material. While the elements produced are rectangular, the setup at Confac the casting setup is interesting, because it is conceptualised on a basis of an analysis and optimisation of *flows* as defined in chapter three. Traditionally, elements are cast on a static casting table, with different workers taking turns in adding the mould elements, the reinforcement and finally the concrete pour to the table. This forces the workers to set up their working station around each mould, perform the task and then move on to the next mould. This constant shift in working conditions prolongs the production, is time consuming and prone to error. At the Confac production line, casting tables are not static, but moveable (figure 1). They are moved around to different stations and specially configured stations provide optimum working conditions for making the mould, adding reinforcement, insulation, casting and a storage shelf for curing. This eliminates the wasted time around logistics of accessing the same station multiple times and frees floor space which would otherwise be occupied by the element while curing. The act of making the moulds is however still manual, using standard or custom built railings or inserts for the casting tables.

Figure 1: Optimized production flow at Confac in Randers.

STATE-OF-THE-ART: SUBTRACTION

Subtraction of material is a method which addresses the potential amorphousness of concrete. Subtraction is the act of controlled removal of material to create a mould, a very well-conceived and conceptually clear means of generating form. A classic example of subtraction is seen in classic sculpting, where a block of stone, wood or plaster is transformed into a bust. Each material has its own technique – incising, carving, pecking, or abrading, each of which will be evident in the final object. This is also the case with subtractive mould making: the process of making the mould, that is the 'fingerprint' of the tool and pattern in which material is carved, is imprinted in the mould material, then on to the concrete cast. This indicates that a special attention to the mould material is essential.

EPS

Expanded Polystyrene (EPS) is widely used for a range of applications in the building and packaging industries, due to its low weight, high compressive durability, thermal properties and low price. But it also has some characteristics which make it suitable for concrete casting.

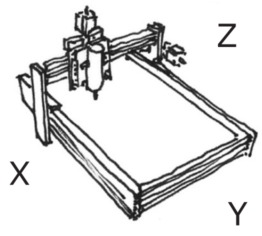

Figure 2: the CNC router works by removing material by means of moving a rotating drill-bit in three directions: X,Y, and Z, within a limited design space.

There are two good reasons for choosing EPS as a mould material. First, EPS is a lightweight material; it can (still) cope with the huge pressure of poured concrete without deforming. Second, because of is low density, normally around 40 gram per litre, it is easy for tools to manipulate it. This manipulation is *subtraction* of material, that is, the controlled removal of EPS from a block, thus generating a crevice in which to pour the concrete.

EPS AND CNC MILLING

One way of performing the subtraction is by means of *milling,* using either a three-axis or six axis robotic arm, moving a spindle with a mill attached to it. While the robotic arm in principle allows for a free design space, the three-axis arm poses limitations in height and direction of the milling. Common for both techniques is freedom in movement on the three axes: X, Y, and Z (Figure 2).

It takes a long time to mill forms that curve freely in three dimensions. Software translates a three-dimensional digital model into machine-code for the CNC router software to read. During this process it generates what is called a *tool path*. Therein lies an important clue as to what the technology actually does: it has a tool which follows a *path*.

The milling head has a fixed geometry (it is either flat or curved) and to approach the form the milling head follow the tool path, cutting laterally through the EPS. When milling or cutting, high material density increases the lateral pressure on the mill, necessitating higher strength in the tools while limiting the working speed. So a lesser density of material results in faster milling speeds.

Once the approximation is complete, an iteration or so-called *pass* is done. Typically two passes, that is, two different tool paths are made, one for a rough cut and one for a fine cut. In the first pass the mill removes most of the excess material, but in the subsequent passes the mill only removes a fraction of the material it is capable of which is a primary cause of the process to being time consuming. The question arises whether it is possible to analyse the logics of the CNC tool path, in order to introduce a restriction which may reduce milling time and introduce some implications for the form; a means to read use the technique not as a post-rationalised necessity, but as the guide in defining the overall geometry. This will be addressed in the case study 'Tool Path' in chapter eight.

UNIKABETON

The research project 'Unikabeton' mentioned in chapter one, utilised robotic CNC milling in order to create amorphous moulds. Small scale tests were milled in wood (figure 3), and in EPS in a building scale prototype (figures 4 and 5). The main focus of the research was topology optimisation of concrete constructions. Topology optimisation is a digital process of moving material around within a design space (a column, beam, or slab), placing material where the forces are and removing it from where they are not. Potentially the process allows for a 70% reduction in the concrete needed and a concrete construction where the flows of forces are visible in the concrete geometry.

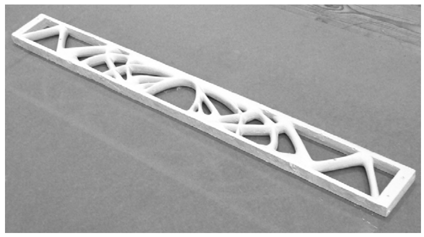

Figure 3: A model scale topology-optimised beam.

In this project, two challenges are identified. First, the manufacturing process of CNC milling was time consuming. As described above, several passes need to be made in order to arrive at a smooth surface and the time needed to perform each pass is dependent on the geometry. In this case the amorphous geometry required a long tool path to complete. A a consequence, only one pass was made, resulting in a finished concrete structure with a coarse, stepped surface. This leads to the second challenge: the surface character, which is problematic both aesthetically and practically, it is difficult to de-mould because the mill rips open the po-

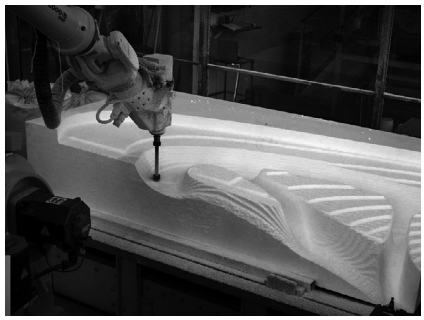

Figure 4: CNC milling of large scale EPS blocks.

Figure 5: Traces of the mill are visible after the EPS is removed

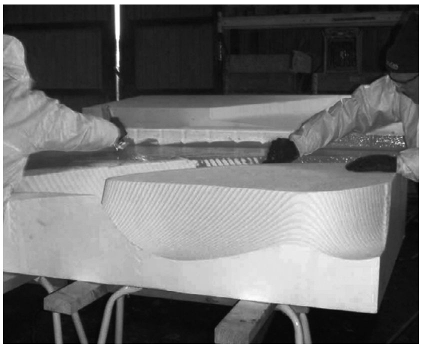

Figure 6: The EPS mould is covered with liquid membrane.

rous structure of the EPS, allowing cement to seeps through the crevices and act as small hooks.

This problem gave rise to another research project entitled 'Tailorcrete', in which a strategy for applying a liquid or rubber membrane was examined to prevent the cement from seeping into the EPS (figure 6).

While both the Unikabeton and Tailorcrete projects did demonstrate that it is possible to generate amorphous forms in concrete, the relations between material, technology and form is problematic. The internal logics of the technology are not utilised, as the CNC mill is used to create complex shapes without any attention to what the best and most optimised use of the technique may be. As a consequence, the number of passes was reduced to just one, leaving a surface that does not tell a story about the relationship between material and technology, but of the problems in the way the technology is used, visible in the stepped surface. In other words, the stepped surface is not a choice, it is a necessity. A case study called 'Under Pressure' which deals with the problematic surface of cut EPS is presented in chapter 9.

EPS AND HOTWIRE CUTTING

The issue of CNC milling being time consuming has led to a research project investigating hot-wire cutting of EPS instead of milling. The low density of EPS and the fact that the material is a plastic which melts at fairly low temperatures makes it possible to do fast, precise cuts using this technique.

Cutting as opposed to milling has the unique feature that the positive remains intact, giving a precise impression of the concrete element which will be created once the negative is filled (figure 7). Equally unique is the fact that the hotwire is linear, which gives a restriction in the possible forms, as the wire cuts into the EPS material. The linearity exists in the direction across the cut, as the forward motion is free. While linearity is restrictive it also introduces a circumstance which may be used architecturally.

The process of hot-wire cutting involves translating the three-dimensional concrete elements into cutting patterns. Two patterns are needed, one for each end of the wire. It also involves a strategy for performing the cuts, as intersections created by multiple cuts influence of what parts the mould will consist.

The technique was developed manually using hand-made templates, extracted from a computer model which is used to guide the cut, but potentially the hand-held cutting is replaced by a robot controlling the hotwire, a technology which is currently under development (figure 8).

Regardless of the way the hotwire is controlled, the surface remains the same and suffers from the same problem that CNC milling of EPS produces; the exposure of the porous internal structure of the EPS where the cut is made.

Similar to CNC milling, research has been undertaken to try to overcome the problem by adding a membrane to the mould prior to casting. In the TailorCrete and Industrialised Individuality research projects plastic or rubber (figure 9) has been used. As mentioned, these approaches are problematic since the concrete surface becomes a mirror image of the mould, also the applications, especially the resin coating are time-consuming, manual labour. The plastic or rubber membranes have a tendency to wrinkle when the concrete is poured. The Industrialised

Figure 7: Concrete cast in hotwire cut EPS with the positive mould in the foreground

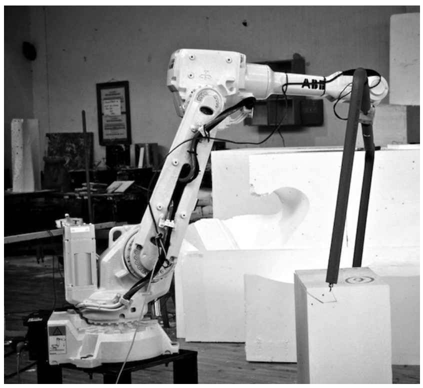

Figure 8: A robotic arm with a hotwire tool, capable of performing precise cuts in EPS

Figure 9: Applying a plastic membrane prevents the cement from seeping into the EPS

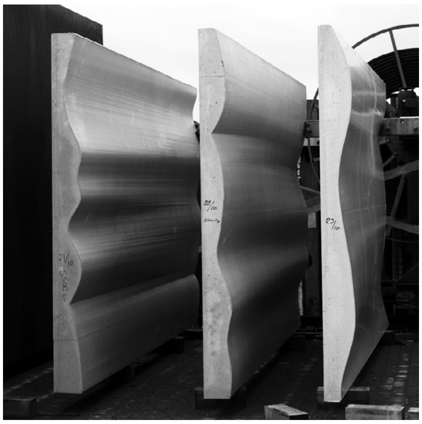

Figure 10: Building scale concrete façade element cast in a hot-wire cut EPS mould.

Individuality project has developed a fourth technique[1] which involves the application of a special non-toxic retarder which is chemically engineered so that it 'sticks' to all sides of the mold instead of flowing down into the bottom.

As with the CNC milling it can be debated whether if the surface treatment is disturbing the tectonic potentials of the techniques, as it is applied out of necessity, thus presenting a limitation to the technique. The treatment of the surface, however, potentially leaves a high surface quality. With plastic or rubber the surface is smooth, and with retarder the surface resembles rough stone. The ability of the retarder to be applied to all sides of the mould, combined with the three-dimensional nature of the forms in concrete available using the hotwire technique, allows for concrete elements with a homogenous and calm appearance (figure 10). This is a quality rarely seen in traditional rectilinear, horizontally cast concrete elements, which are only retarded on the bottom surface, making them appear more like a screen than three-dimensional stone.

Despite the potentials in the technique to offer amorphous concrete elements, no concrete buildings have been proposed, let alone built, using this technique. This lack of reference as to what a concrete structure cast with hotwire cut moulds could be is addressed in the case study 'Kofta' in chapter seven. Specifically, the potential relations between hotwire cutting and architectural form are investigated.

STATE-OF-THE-ART: TRANSFORMATION

A radically different trajectory is the method of *transforming* a material to form a casting mould.

As the word implies, form is generated by a deflection, creating a non-linear crevice or surface on which to cast. The advantages of this approach

1 The research is undertaken at the Aarhus School of Architecture by Professor Karl Christiansen.

are twofold: first, the amount of material is held constant, meaning that in principle the laborious task of subtracting or adding material is unnecessary. Second, the deflection of the mould is potentially non-linear, resulting in amorphous formed concrete. In other words, a lot of form is given using very little effort.

Current research makes use of a subset of transformation: *deformation* and includes three trajectories: fabric casting against gravity, spray-casting on a flexible membrane and spray-casting against inflated membranes.

FABRIC CASTING

Casting in fabric has the special circumstance that the weight of the concrete is a contributor to the form. A fabric is suspended between supports and as the liquid concrete is poured, the weight causes the textile to deflect. The shape of this deflection may be guided in part by the way in which the fabric is suspended, attached, or otherwise manipulated (figures 11 and 12). But the gravitational pull on the concrete will always be visible in the nature of the deformations (figure 13). This is a technique where the circumstances are visible and readable in the cured concrete element, in that the restrictions caused by the logics of gravity and the nature of fabric are the direct cause of the element. Adding to this tectonic quality is the fact that the surface of the textile is translated to the concrete, which generates a highly tactile surface[2].

The challenge in this technique is precision. While the attachment of the fabric to the supports can be controlled, the overall geometry of the concrete is both difficult to predict and is inherently double-curved which makes it difficult to adapt. This lack of precision may become problematic when several fabric cast members are connected, and in situations where fabric cast elements are to meet industrializes, rectilinear building

Figure 11 Fabric formwork: Underlying plates influence the geometry of the casting

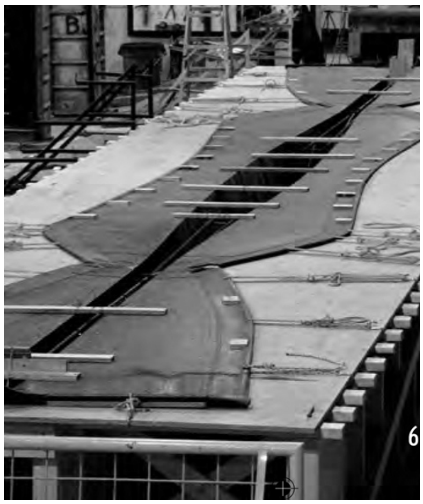

Figure 12: Fabric formwork: Pre-stressing of the fabric influence the geometry of the casting.

2 West, M., Araya, R.: 'Fabric formwork for concrete structures and architecture', Int. Conf. Textile Composites and Inflatable Structures, Barcelona, Spain, 5-7 October, 2009

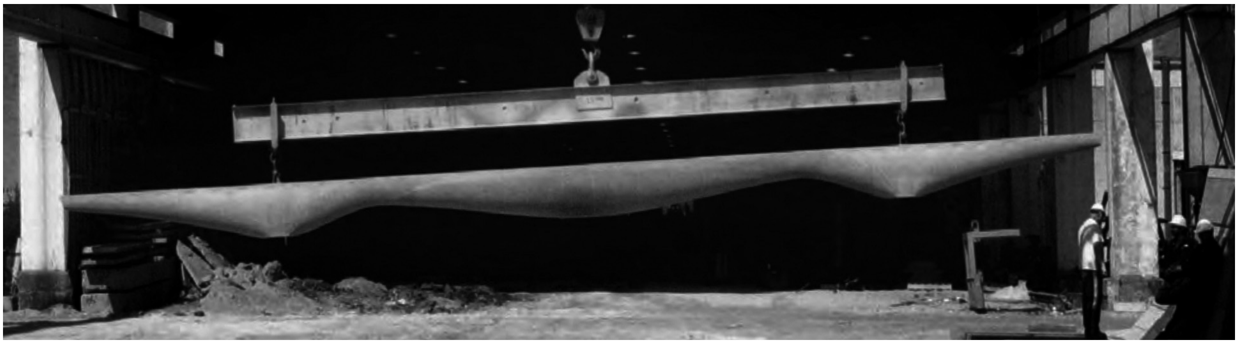

Figure 13: A fabric cast, optimized beam

components, such as windows and doors.

The fabric has a lack of stiffness which prevents other, more precise transformations from being used. The case study 'Hello World' in chapter ten investigates if a more rigid mould material transformed by means of *bending* or *folding* rather than deformation may help re-introducing precision.

HORIZONTAL CASTING TABLE WITH A FLEXIBLE MEMBRANE

A more tightly controlled technique is concrete spray-casting against a horizontal membrane, adjustable by means of a matrix of pistons (figure 14). This allows for the digitally controlled deformation of the membrane, creating curvature in all directions in a matter of seconds as opposed to hours if the geometry was to be CNC milled. [3]

This ability for the flexible mould to be produced very quickly can take any form, potentially allowing for mass-customisable, non-linear concrete elements. When focusing on concrete as a material, however, there are two problems with the technique: first the technique is challenged by the property of concrete which fabric casting uses to its benefit - the liquidity. Concrete is a viscous material which means that it has to be applied in a thin layer to adapt to the mould. This in turn means that

3 The technique is developed by the Danish company ADAPA in 2010

the technique is limited to producing façade panels, not structural elements (figure 15).

The second problem, which is caused by the material property, is the incapacitation of the mould. The curing time for concrete is 24 hours, during which time the mould is occupied. This makes flexible membrane casting a very slow technique and unfeasible in a large scale concrete production. To overcome this challenge, attempts have been made to introduce an intermediate step of making a casting of the flexible mould in polyurethane foam. This step introduces an increase in the use of resources and only enables one-sided moulds to be made. From a tectonic

Figure 14: Flexible casting table. Digitally controlled pistons allow a membrane to change its shape

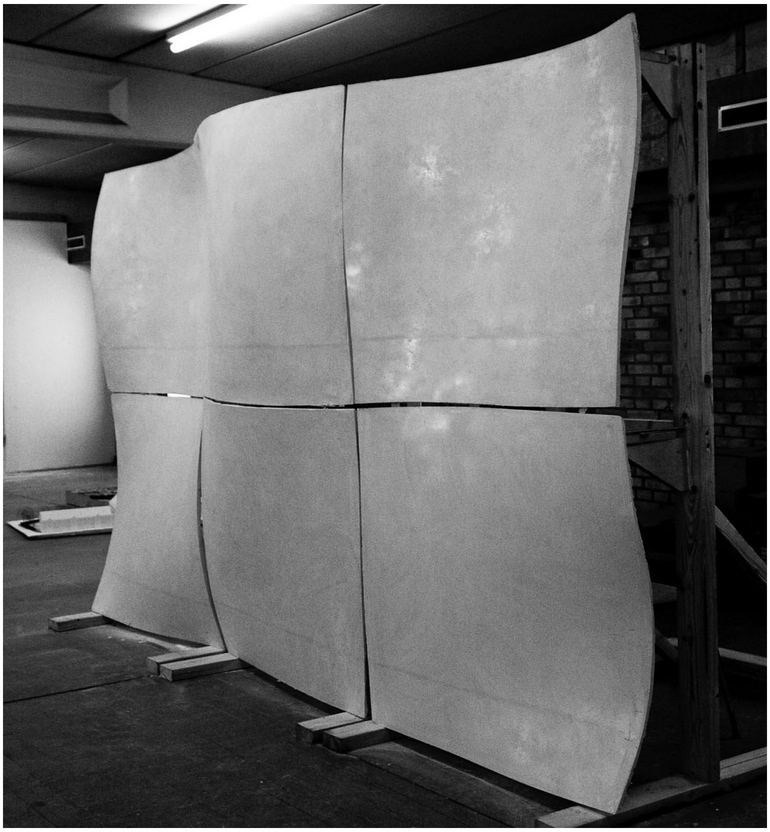

Figure 15: A constellation of thin, fiber-reinforced elements. (ADAPA)

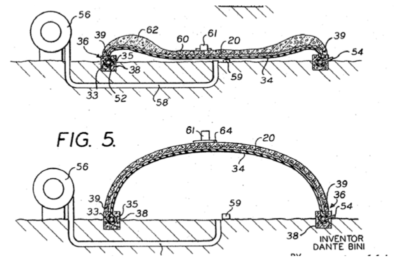

Figure 16: Inflatable mould technique. Patent application drawing by Dante Bini, 1969

Figure 17: Bini shell constructed in 1974 at the Killarney Heights Public School

point of view, this is a restriction which works against the logics of the technique and the story of the fabrication is obscured. The case study 'Under Pressure' presented in chapter nine investigates how a quite different technique may be used to address these limitations.

INFLATED MEMBRANES

The last technique which utilises deformation is similar to the flexible casting table, but instead of deforming the membrane using pistons, it is inflated like a balloon (figure 16). The geometry is restricted to domes and while the form generation is extremely quick and a shell can be erected in about three hours.[4] With the mould acting like a balloon the application of concrete and reinforcement is hard to control. The spray-casting technique leaves an uncontrollable surface, giving the structure an appearance of randomness (figure 17). Lack of precision, in fact, has turned out to be an issue, not in the surface, but in the overall geometry. If the form of the balloon thus deviates from the compressive arc during the curing phase, the structure collapses, which several shells have done[5].

The technique is interesting in that it allows for large spans to be covered with very little concrete. This was also the case in the compression-only structures created by Felix Candela, but the Candela shells were cast against wooden scaffoldings which were laborious to produce. The geometry of the concrete shells are restricted to circular or ellipsoid shapes, giving the shells an appearance which is reminiscent of the appearance of rationalisation found in buildings made from mass-produced concrete elements. The case studies 'ReVault' and 'PlayVault' in chapter eleven and twelve, respectively, investigate how algorithmic and parametric computation combined with a novel casting technique can allow for the construction of complex-shaped compression shells.

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4 Bini, D.: Binishells, S.p.A. Method for Erecting Structures, U.S. Pat. 3,462,521, 1968.
5 Grad, Paul. "Bini shell Collapse." Engineers Australia 63 (8 March 1991): 27-28.

CASTING WITHOUT A MOULD

Finally it should be noted that it is possible to cast concrete without a mould by large scale 3D concrete printing, bypassing this categorisation all together (figures 18 and 19). This trajectory is investigated by several research projects[6], the results of which indicate that the technique is still in its infancy. Most notably, the surface is uncontrollable, and the geometry is severely restricted by the nature of the technique. That is not to say 3D-printing is not promising, but that the technique is not perfected enough to undergo evaluation in this context.

Figure 18: 3D printed concrete (image copyright the European Space Agency)

Figure 19: Concept model for a 3D printed moon base structure. (image: tested.com)

CONCLUSION

Based on the assessment of current research six concrete casting techniques are identified, in which the tectonic relations between material, technology and form may be strong: 3D printing, CNC milling of EPS, hotwire cutting of EPS, inflated membranes, flexible casting tables and fabric casting. When considering these casting techniques together with the account of tectonics in chapter two and the findings regarding the art of making in chapter three, one can concluded that the tectonic potentials are stronger with some techniques than with others, and that not all techniques can enter into an industrialized environment, to allow for mass-customized concrete elements with:

- complex geometry
- potential for mass-customization
- economical production in terms of time and use of resources
- high degree of precision
- potential for digitalization

6 Research in 3D-printed concrete is undertaken at the University of Southern California and Loughborough university. The European Space Agency is experimenting with large scale printing for a moon base from a mixture of moon dust, magnesium oxide magnesium oxide are two words and salt.

Consequently, the inflatable membrane technique is less relevant in this research. Strong relations between material, technique and form were found in three casting techniques. The two *subtractive* techniques: *CNC milling* and *hotwire cutting* of EPS were found relevant to the research because they both allow for the making of precise, amorphous concrete elements with a complex geometry within a digital production setup. *Textile casting* was found relevant because *deformation* replaces the laborious mould crafting process.
One can also concluded that these three techniques have problems. With CNC milling, the biggest problem is found to be the slow milling process. A problematic surface was a common problem for CNC milling and hot-wire cutting. With textile casting, the problem was a lack of control over the geometry.
These problems with the technique and material may be seen as gaps in the relation between material, technique and form and it is these gaps the case studies set out to address. As described in chapter two, a distinction is made between *concrete tectonics* and *mould tectonics*. With regard to this distinction, the gaps exist between the material, technique and form in the making of the *mould* and it is these gaps that will be addressed. In other words, the case studies will investigate *mould tectonic relations*. The following is a summative outline of the six cases and their starting point:

Chapter seven: Kofta

The case study proposes a concept for concrete structures cast with hotwire cut moulds, given a specific brief. Specifically, the potential relations between hotwire cutting and architectural form are investigated.

Chapter eight: Tool Path

In the case study long milling times when CNC cutting EPS moulds are addressed. A mapping of the logics of the CNC forms the basis for investigating how these logics may define the geometry and reduce milling times.

Chapter nine: Under Pressure

In the case study ‘Under Pressure’ it is examined if the isotropy in EPS can be sustained when it is used as a casting mould. At the same time it deals with the problematic surface of cut EPS. Further, it addresses the limitations found in the flexible membrane / horizontal casting table technique.

Chapter ten: Hello World

The case study ‘Hello World’ is the development of a novel casting method, in which folding is used. The case investigates if a more rigid mould material transformed by means of *bending* or *folding* rather than deformation may help re-introducing precision, which was problematic in the textile casting technique. Further, the case investigates how computation and digital fabrication may be used to describe and manufacture complex casting moulds.

Chapter eleven: ReVault

The case study ‘ReVault’ has an expanded focus on the digital design and production in the construction of complex compression-only structures in which the use of concrete is optimized in a fashion comparable to the work done by Felix Candela and Dante Bini. For this purpose algorithmic and parametric computation combined with the technique developed in the Hello World case study are developed and tested.

Chapter twelve: PlayVault

The last case is a continuation of the ReVault study, introducing increased geometric complexity and the use of fiber-reinforced concrete.

PART III
CASE STUDIES

CHAPTER 7: KOFTA

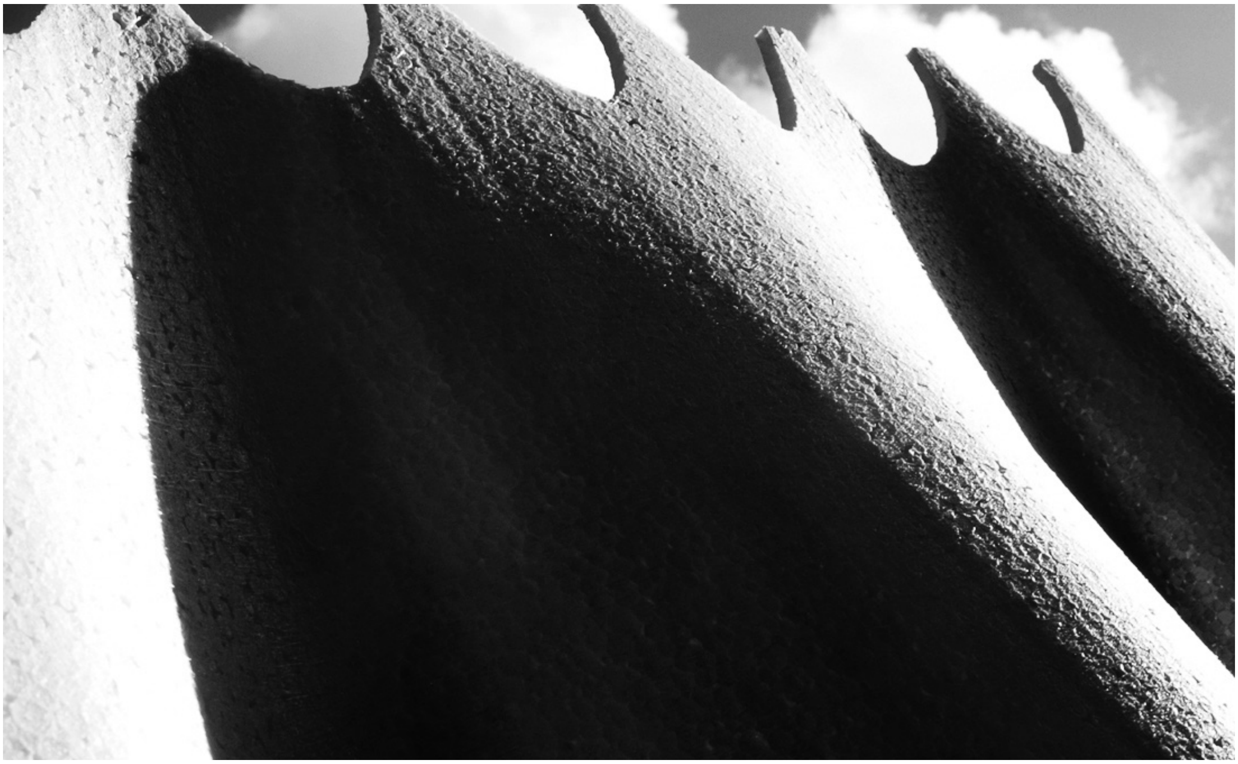

Figure 1: 'Kofta' concrete power mast proposal. EPS scale model

INTRODUCTION

The cast study 'Kofta' is the investigation of an *existing*, *subtractive* technique. Building on Kenneth Frampton 's concept of the *poetic construction,* an *elaborated design proposal* is made in order to investigate the architectural potentials of casting concrete in hot-wire cut EPS. This technique was developed recently and no examples exist to illustrate how the tectonic implications of the technique may be used architecturally. This was investigated by responding to a Norwegian competition concerning the re-design of high-voltage power line masts. The proposal was made in collaboration with Professor Karl Christiansen, who had previously developed the EPS hot-wire cutting and casting technique and the proposed design drew on findings from this research.

Before proceesing to the actual case study, an illustration of the geometrical forms and surface achievable with this technique is offered. This was investigated in a workshop 'The Bench' (figure 2) which was part of the Concrete Tectonics Studio at UTS, Sydney in 2011 in collaboration with Professor Karl Christiansen and Associate professor Kirsten Orr.

Figure 1: 'The Bench': discrete concrete elements cast in hot-wire cut EPS moulds. Positives of the moulds visible at the far left.

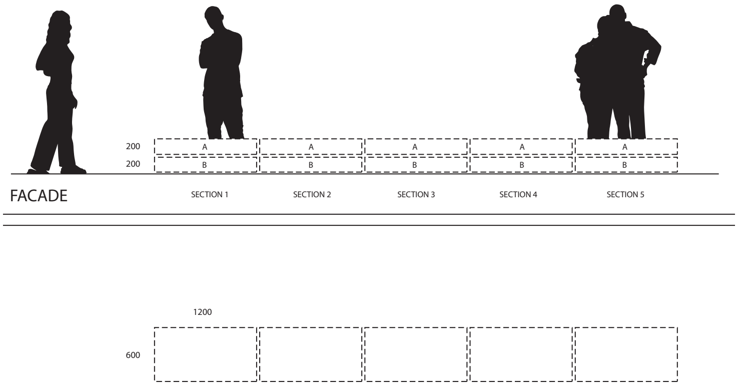

Figure 3: Global design space.

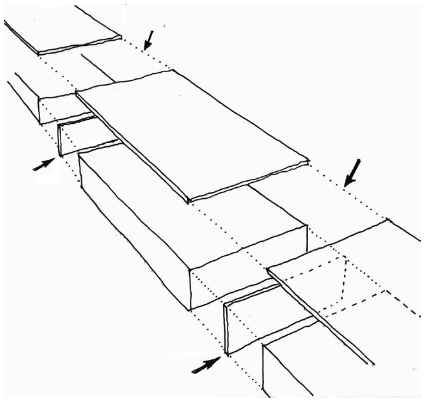

Figure 4: Local design space.

THE BENCH

The goal of the experiment 'The Bench' was to investigate two different surface finishes of concrete cast in hot-wire cut EPS, and to create a continuous form across multiple elements. A global and local design space was established, in such a way that linear cuts could be made to make local cuts while maintaining an overall geometrical connection across elements (figures 3 and 4). These connection were made by using the same template on neighbouring elements. Model scale hot-wire cuts were made to improve the geometry (figure 5) and discuss a strategy for surface treatment.

It was agreed to apply retarder to the sides of the moulds and cover the bottom in plastic, which translates into a smooth surface top and rough sides of the cast element. Full scale moulds were cut, treated with either plastic or retarder, and cast (figures 6 and 7). The result demonstrated that high precision, a continuous geometrical form, and agreeable surface is achievable using this technique. (figure 8)

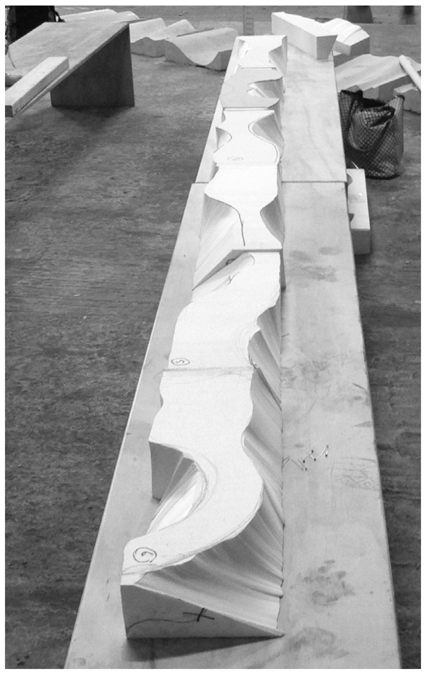

Figure 5: Sketch model in scale 1:10

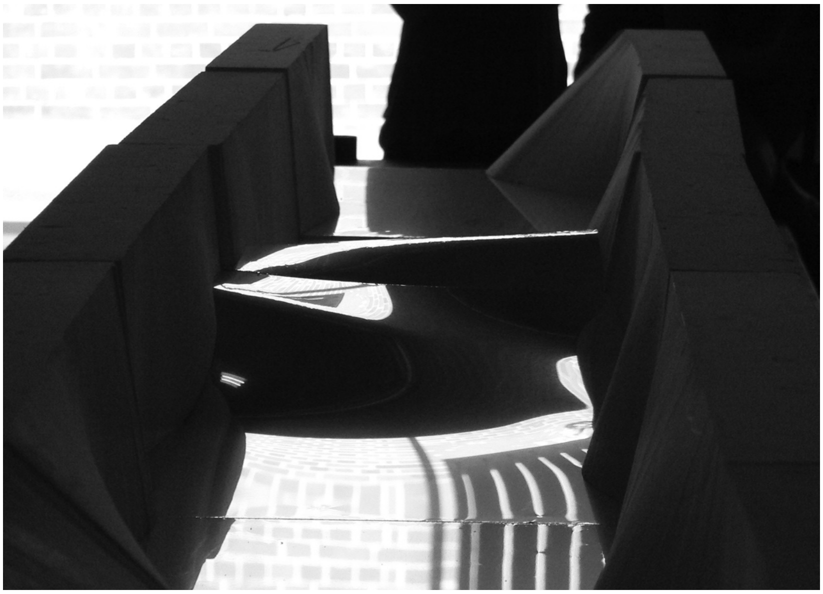

Figure 6: EPS mould. Retarder applied to the sides, plastic film in the bottom.

Figure 7: The moulds after concrete pour.

Figure 8: Geometrical form and surface quality of the retarded surfaces.

THE COMPETITION

The competition was set forth by the national Norwegian energy company Stattnet[1]. The company was planning a new, high voltage, power line to the northern part of the country, allowing CO_2 free electricity from the water turbines in the south to replace oil based power generation currently in use in the north. Such infrastructure has an impact on the environment, hence the competition, in which Stattnet asked for solutions which were more aesthetically agreeable and thus less intrusive in the grand Norwegian nature than the traditional steel masts (figure 9). Specifically, the company asked for designs which did not necessarily present as little minimal visual impact as possible, as is the case with the steel masts. On the contrary, the task was to design a mast that would be able to enter into a dialogue with a specific site. The mast was not to be seen as a generalised type which would be used for the entirety of the new power line, but one to be applied in a few, specific locations where natural or cultural qualities were significant. In other words: a mast with sculptural qualities. The site chosen for the competition brief was a crossing between the power lines and a major road in the Norwegian municipality[2] of Balsfjord. Beside the road, a lay-by serves as a meeting point for the local Same-community, culminating in an annual cultural festival (figure 10).

The terrain in the area is undulated with a surface of partly exposed rock, partly covered with moss, bushes and small trees. This landscape is contrasted by a view to the typical Norwegian mountains in the distance (figure 11). The mountain tops have a softness to them as opposed to many other mountain ranges, e.g. the Alps.

The brief also stated functional requirements which had to be met. These included the number of power cables to be suspended, height in

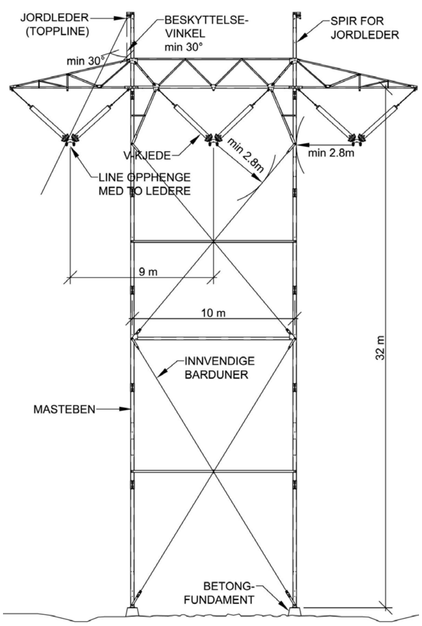

Figure 9: Drawing of steel construction power mast currently used in Norway.

1 Source: Competition: Skulpturmast på Heia - Konkurrensedokument.pdf (Competition brief) http://www.statnett.no/Documents/Om_Statnett/Forskning%20og%20innovasjon/Skulpturmast/Konkurransedokument.pdf (Visited 12-03-2013)

2 In Troms Fylke (Troms county)

Figure 10: The site: a lay-by where a new high-voltage power line meets a major road

relation to ground level and the spacing of power cables, as well as the overall construction being maintenance-free.

Three conditions listed in the competition brief pointed towards the use of concrete. The first a request for a mast to be conspicuous as opposed to inconspicuous, which, according to the competition brief, is the aim of traditional steel masts.

The second was the specific request for a design which was unique , that adapted to the characteristics of the environment, and was in dialogue with local culture.

And thirdly, concrete is capable of meeting the requirement for a zero maintenance solution.

CONCEPT

Figure 11: Terrain typical of Troms Fylke

The overall concept was derived from an interpretation of the place and of the culture. In terms of the place, any construction becomes small when measured against the mountainous backdrop. But when measured against a human scale, a power line mast is large. With regard to culture, a contrast is found in the cone-shaped tents, which represent a geometrical sturdiness and heaviness, as opposed to their construction which consists of a delicate framework and an enclosing membrane in fabric and thus appear light. On the basis of this assessment, a concept was devised which built on two dichotomies: one between *small and large*, and one between *light and heavy*.

In order work with the 'small versus the large' paradigm, an initial concept of a concrete wall was considered. At 30 meters in height and the

Figure 12: The overall geometry gradually changes from an approximated sine curve at ground level to a straight line at the top.

double in width, a solid surface as opposed to an open steel mesh would appear vast when measured against the human scale.

Even though concrete is heavy, a planar wall of such dimensions would need to be of an immense thickness to withstand wind loads. One of the advantages with hot-wire cutting, however, is the possibility to introduce curvature in one direction. If curvature is established vertically, the mast would become stable. At the same time, modulation of light and shadow across the surface would create the impression of lightness of the otherwise heavy concrete.

This was developed into a concept for a concrete wall, made up of 74 individualized concrete elements. At ground level, the wall took shape of an approximated sine curve. From the ground and upwards, the planar cross-sections would morph, ending in a straight line at top, where six power line mounts were to be fitted (figure 11).

Owing to both the shape and the self-weight, the mast would be able to resist both lateral and vertical forces. As such, the concept aimed to establish a closed relation between form and construction, similar to the one found in the Sydney Opera House, in which the construction would be coherent with the form. When measured against the enormous land-

Figure 13: Photomontage of the ‘Kofta’ structure

scape, the structure would appear small, while in comparison to the human scale it would be enormous, yet not overbearing. The continuous form and lack of repetition would give an impression of lightness of the structure and at the same time the wall would serve as a backdrop to the lay-by, enhancing the identity of the Same culture (figures 13-17).

As such, the structure was conceived to add value beyond that of presenting a support for the power lines. A value seeking to enrich, underline and provide identity to the specific site by means of its presence.

CONSTRUCTION

The moulds would utilise the hot-wire cutting technique using data obtained from a digital model from EPS blocks and cast vertically. This would take place in the production line of a factory, similar to the ConFac production. The maximum size of each element would be 10 x 4 meters, defined by constraints in transportation. Sizes would be regulated and elements would be cast with internal EPS inserts to reduce the weight to below 35 tons (figure 18).

After delivery, the elements would be assembled on site with a crane, resting directly on the rock and anchored if necessary. The detailing would include fitting metal brackets on top of the concrete wall to meet the power cable sus-

Figure 14: Site plan. Scale 1:2000

Figure 15: Model photo: mast seen from the front

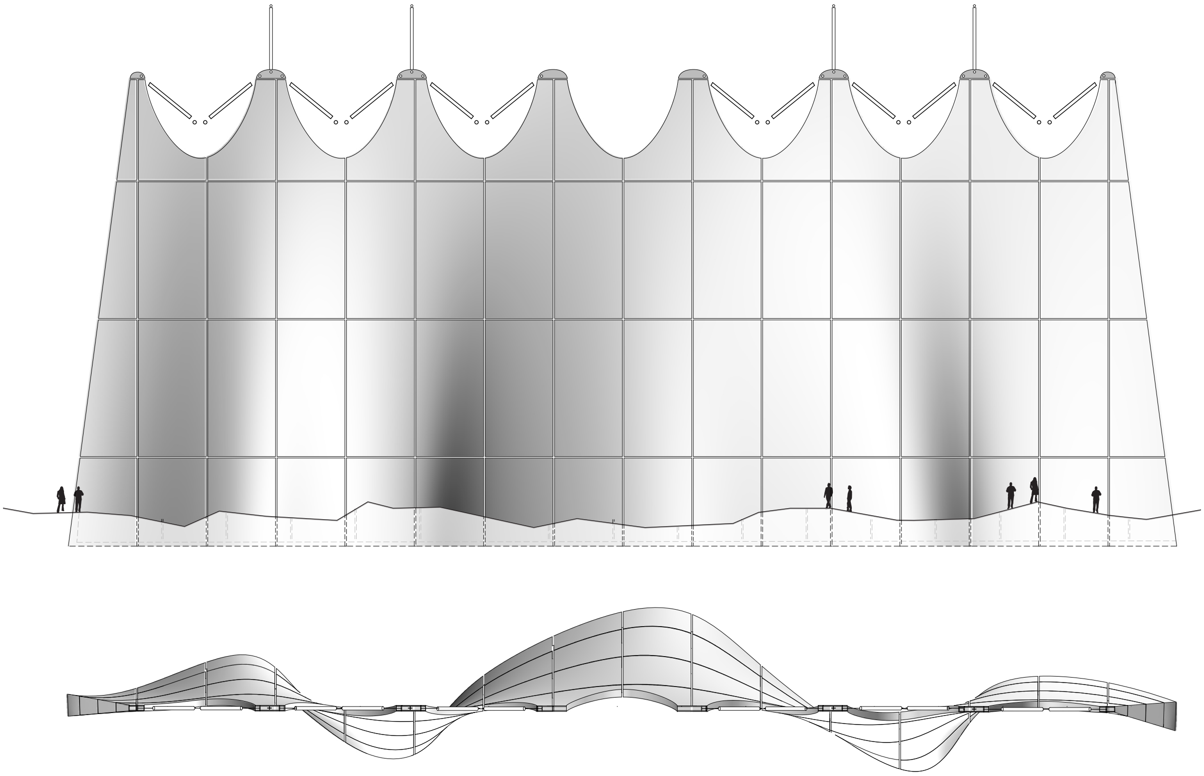

Figure 16: Plan and elevation of the Kofta mast. Scale 1:500

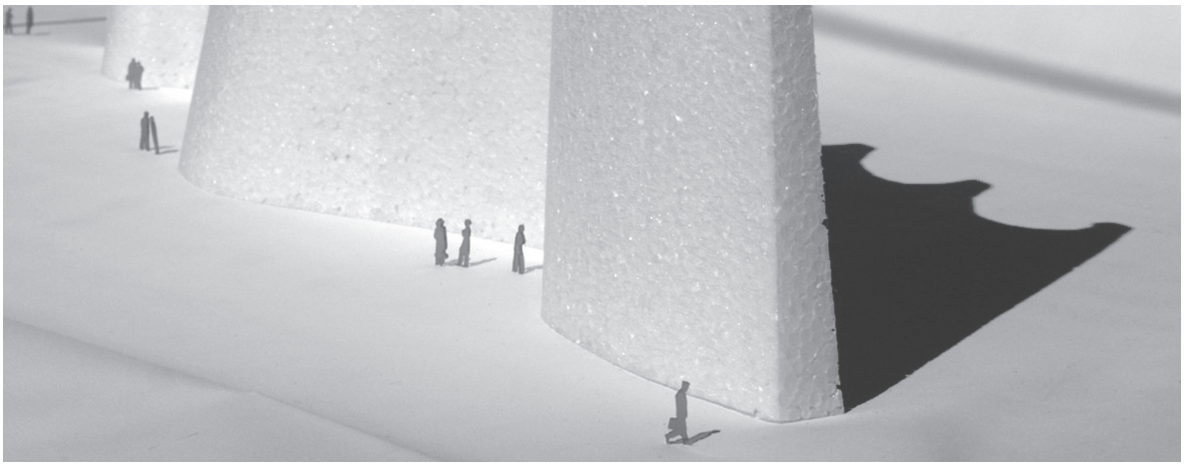

Figure 17: Model photo: curved lower part of the mast

pensions (figure 19).

The surface would be treated with a retarder, giving the surface a stone-like character which over time would be covered in the same types of lichen that grow on the surroundings rocks.

INDIVIDUALITY

The individuality of the technique would allow for designs relating to different sites. Hence, it would be possible to perceive and interpret a place with respect, but without the mast being self-effacing. Therein lies the potential for a constructions which emphasize various surrounding features and enriches the local identity.

Other typologies could be defined, manifested as many individual masts. The types could be mixed, tailoring the constructions to specific sites and purposes, formal as well as functional. Masts would be part of the same family and use the same constructive and material logic, but not identical.

In order to illustrate the idea of types, two additional types suggested, each responding to different locations: the Gate and the Fork (figures 20-23).

CONCLUSION

While the brief was somewhat atypical and not a building in a traditional sense, this case study represent an approach, which could be applied in other, more traditional competition scenarios. As such, the most important finding in the case study lies in the demonstration of how coherence between form and construction may occur with mass-customised concrete elements. One can conclude that the technique, namely the ability to create curvature in one direction while maintaining linearity in the other, together with the ability to differentiate each concrete element, was central for the development of the proposal. This allowed the hot-wire cutting technique to give rise to at least three different types and innumerable variations of these types, each with bespoke characteristics, which were developed whilst taking place, culture and function into consideration.

In the Kofta example, an abstract relation to the culture of the local inhabit-

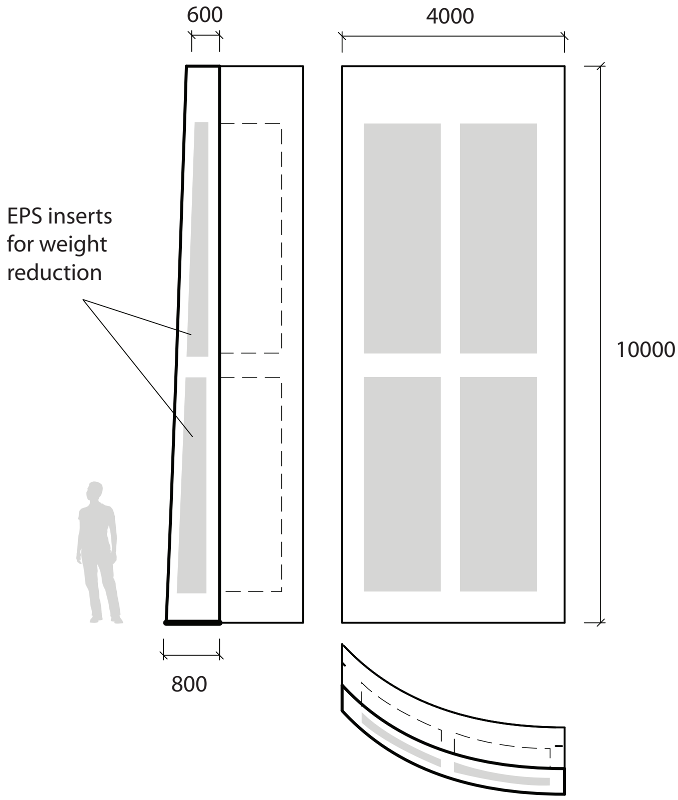

Figure 18: Plan and elevation drawing of a concrete element form the Kofta Wall. Scale 1:100

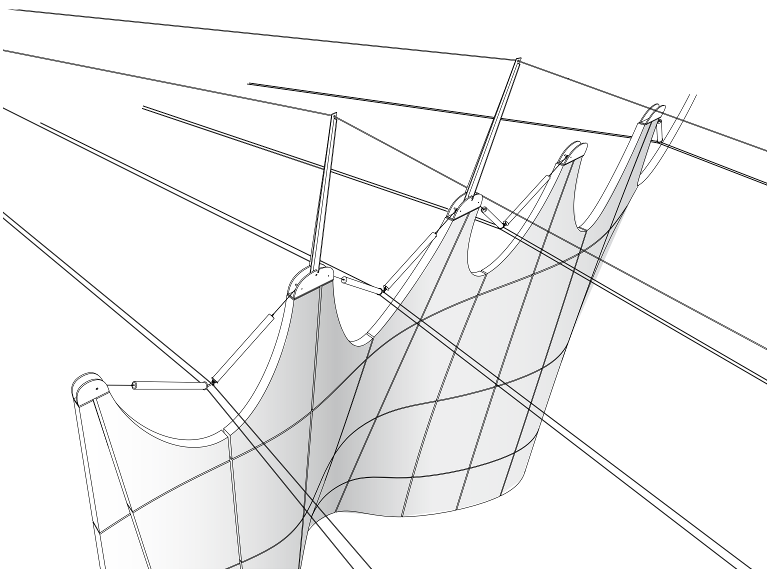

Figure 19: Power cable suspensions fixed to metal brackets on top of the concrete wall.

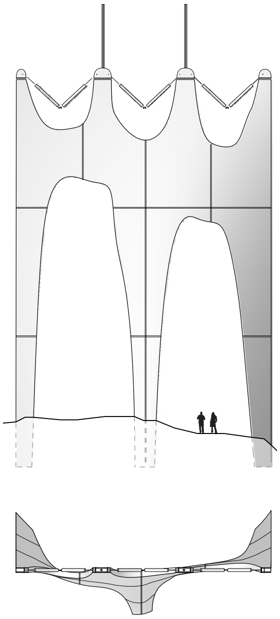

Figure 20: The Gate

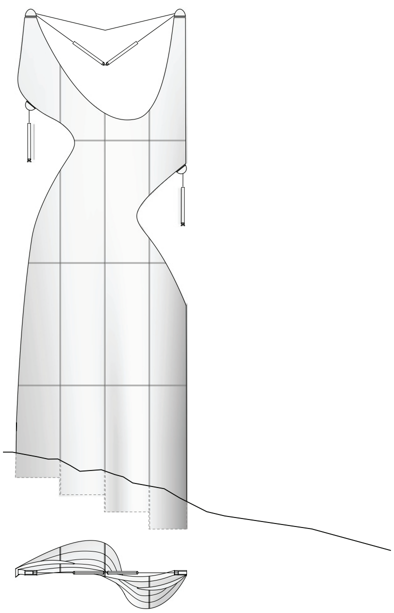

Figure 21: The Fork

ants, as well as a dialogue with the vastness of the surrounding landscape was proposed.

Put differently, it was possible to define an architectural intention to correspond with the possibilities of hot-wire cutting and EPS. Out of the competition brief, two main objectives were found: the design should do the exact opposite of the existing pylons, that is, step forward and go into dialogue with the landscape, as opposed to blending into the background. Hence it may be concluded that the technique is a means of establishing a dialogue between formal intentions and possibilities in the mould making.

With regards to the technique, it is concluded that the realisation of the proposal is realistic, as the logics of hot-wire technology allow for a high speed manufacturing process and with the advancement of robotics, for digital design to production and mass-customization. The case did, however, not address in detail aspects concerning digital design of production as well as resource-optimization. Also, the problems relating to the EPS surface were not addressed. The addition of a retarder solves the release-issues which exist when casting against hot-wire cut EPS, but it also obstructs the relation between technique and form. This problem is investigated in the case study 'Under Pressure'.

A special feature of the technique is that models are produced using the exact same technique as would be used in the realisation. This provides a rare opportunity to evaluate the performance of the design in the light of making, which is unavailable when making models in other materials, as the manipulation of these materials is done with different means than the ones applied in production.

Figure 22: Concept for a mast to with three legs for easier placement in rugge terrain.

Figure 23: Concept for four slightly different masts, ‘walking’ through a valley.

CHAPTER 8: TOOL PATH

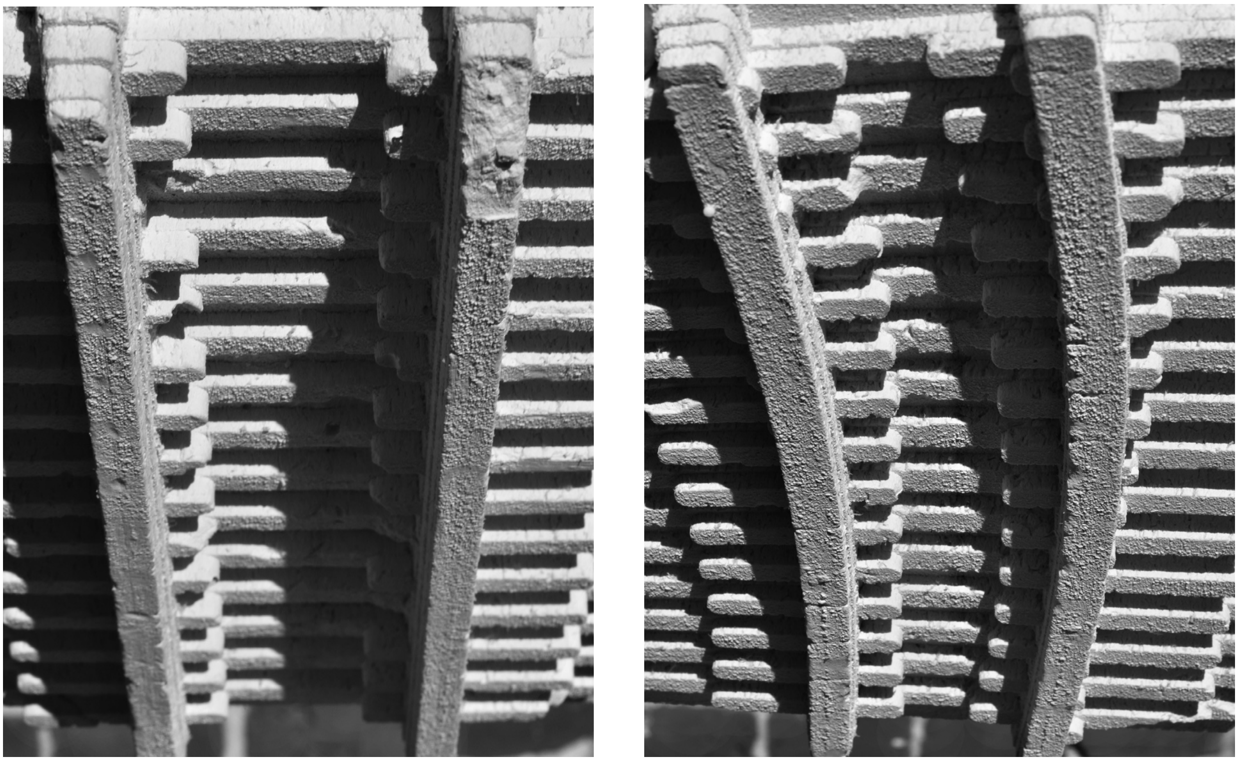

Figure 1: Plaster scale model of concrete roof element casts in CNC milled EPS.

INTRODUCTION

The *tectonic potentials of an existing mould making technique* is the topic of the case study. Apart form the initial choice of CNC milling as this technique, the goal of the case study is to investigate how geometric form can occur as a result of *material considerations* and the *process of building,* as proposed by Kenneth Frampton. CNC milling was used in a recent project: the Big Belt House by Massiearchitecture (figure 2),[1] due to its ability to generate complex mould geometry. If analysed from a tectonic perspective, the way CNC milling is used in the Big Belt House project presents two problems.

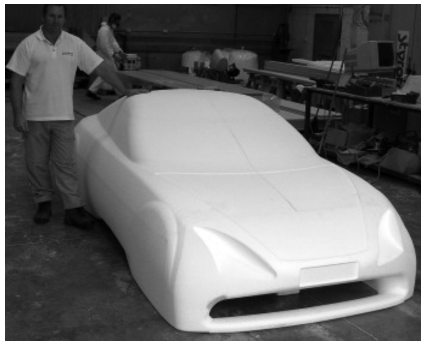

Figure 2: a CNC milled, full scale mock-up of a car

FORMAL IMPLICATIONS OF CNC MILLING

The first problem is a formal one. While the form of the house is derived directly from a reading of the surrounding topography, thus pointing towards the amorphous, the EPS moulds for the frames are single curved and flat sided. This means that the CNC milling process is used to mill a one-dimensional line forming the outline of each mould only. This is a reduced use of the technology and it might have been quicker with a water-jet or laser cutting in other materials. In other words, the moulds generated are dictated by a formal concept rather than the technology itself. As a result, the form is indifferent to the technology. Since the form is not informed by any particular logic in the use of the technology, the milling process is time consuming and the choice of technology is not apparent in the final form.

Figure 3: Mass-customised concrete moulds allow for an overall geometry of the Big Belt house which allows it to enter a dialogue with the surrounding hills.

These two objects are amorphous, but still the result of a pure formal idea, which means the optimum use of the technology is not considered. An analogy to this is found in the car industry, where CNC milling is used

Figure 4: Big Belt House under construction. CNC milled EPS moulds used for casting concrete frames.

1 The Bigbelt house was completed in 2001 by Massiearchitecture. It is features In Liquid Stone pp. 182-185

to showcase the form of a whole car (figure 4). This process is very time consuming, since the drill-bit has to approximate a landscape-like form, which requires that material is carved away in several so-called passes, where each pass is a better approximation of the form than the previous.

CNC MILLING AND TIME

The second problem is time. When the form is fixed, the only way of reducing milling time is making the cutting path coarse, causing an equivalent coarse concrete surface. Added to this the drill-bit also rips the polystyrene beads, creating a flossy surface which is also translated to the concrete. In the case of the curved wall and the sink, this becomes apparent in the concrete surfaces.

When concrete is cast against EPS that has been sliced with a hot-wire or milled with a CNC miller, the hydrostatic pressure will force cement into these crevices making it very hard to dismantle the mould and leaving a coarse and uncontrollable surface. As described in chapter six, projects currently using EPS as a mould either accept the surface and the release problems, or post-treat it with an epoxy or similar hard coating.

This case study investigates if an inherent *logic* or *binding* within the CNC technique may reduce the milling time, while utilising it as part of the design.

A small scale CNC mill was acquired and used in the investigation along with open source machining software[2], in order to be able to learn and understand all parts of the CNC milling process.

Through the setup of the CNC miller and subsequent 3D- modelling and milling of simple objects, it was established that the position of the CNC machine's axis is controlled by a virtual tool path, translated into physical movements of the CNC mill (figure 5). The tool path basically describes the surface of a given 3D model in a series of lines representing

2 The Linux based software EMC2 was used.

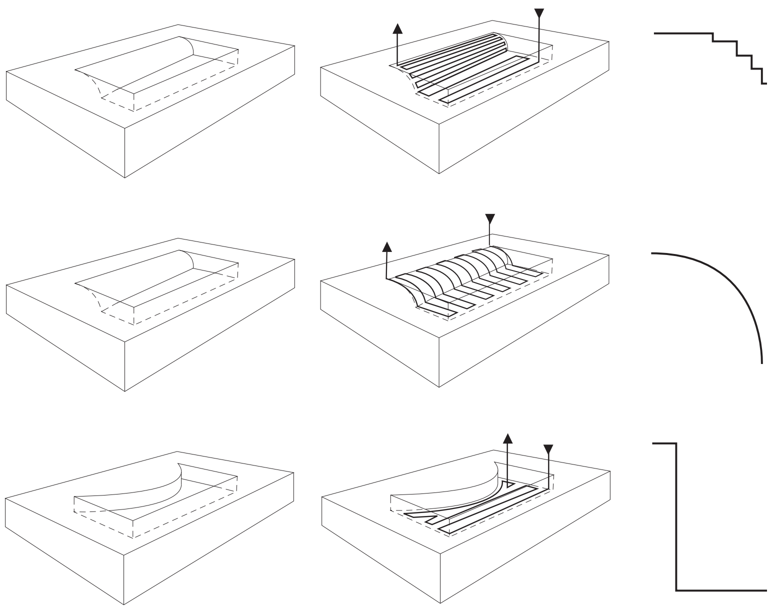

Figure 5 top: Milling a curved geometry requires a long path, to preserve a smooth surface.

middle: orienting the tool path may improve milling speeds and surface quality, depending on the orinetation of the curvature.

bottom: restricting curvature to the x-y plane significantly reduces milling time.
(milling time is described as the length of the path)

the path the mill needs to travel to carve out material. A piece of software automatically calculates the path on the basis of a 3D model. As the CNC miller is oriented top-down, the curvature in the x-z plane is slow to mill and leaves 'steps' in the mould. (figure 5 top). Some optimisation can be achieved by orienting the path across the topography (figure 2 middle), but the fastest milling time is achieved by restricting curvature to the x-y plane (figure 5, bottom).
The investigation builds on this observation and makes the case for altering two aspects of the typical use of the CNC technology:
1) the tool path is defined manually as opposed to computer generated.
2) the geometry is restricted to curvature in the x-y planes

THE INVESTIGATION

These restrictions are imposed on an imaginary concrete element, inspired by the traditional TT plate, a slab with two embedded beams (fig-

Figure 6: the TT-plate, a widely used type of concrete element

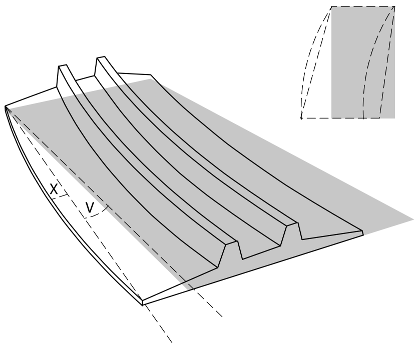

Figure 7: A mass-customizable concrete slab with two beams

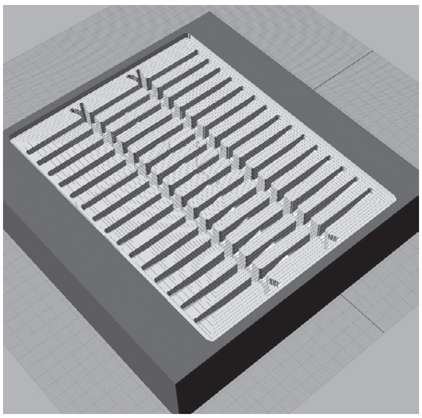

Figure 8: Digital model: 200 x 200 mm. Defined with a direct relationship to the milling path.

ure 6). While the standardised TT plate is linear, the study will try to define how it may be customised in a way suitable for the CNC milling technique. If the customisation is to happen in the x-y plane, a natural transformation would be to skew and/or bend the element. Variables include the side angles (V), allowing the element to take on the shape of a trapezoid. Further, the directional freedom in the x and y axis will allow sides to curve, for instance by altering the distance (X) (figure 7).

The concept model is translated into a casting mould by means of redefining the geometry as a tool path for the CNC miller to follow. The process of milling creates voids representing the negative spaces for the plate and beams. In other words, the initial geometry that is conceptually two beams and a plate is not interpreted as such, but rather as a landscape of canyons and mountains (figure 8).

As described in chapter six, a second pass, the fine cut, is usually applied to create a smooth surface. In this investigation, it is omitted, leaving a 'stepped' model, something that is not considered to be agreeable. With good reason; it looks unfinished and coarse, and it obscures the planar faces on the initial geometry. To establish a closer link between form and technique, and to further emphasize the structural performance of the slab, the *initial geometry*, is re-evaluated as a number of cuts the width of a milling head and of varying depth, as opposed to a topology which is translated by the computer into a geometry with arbitrary steps. In this case the 'steps' are effectively the same as beams: areas where there is more material and thus a higher structural integrity.

The digital model forms the basis for making the tool-paths. The model is then milled from an EPS block and cast. Two models were made to illustrate the differences in geometry when the slab is linear or bent by introducing curvature in the x-y plane.

CNC milling operations of both the initial geometry (200 x 200 mm) and

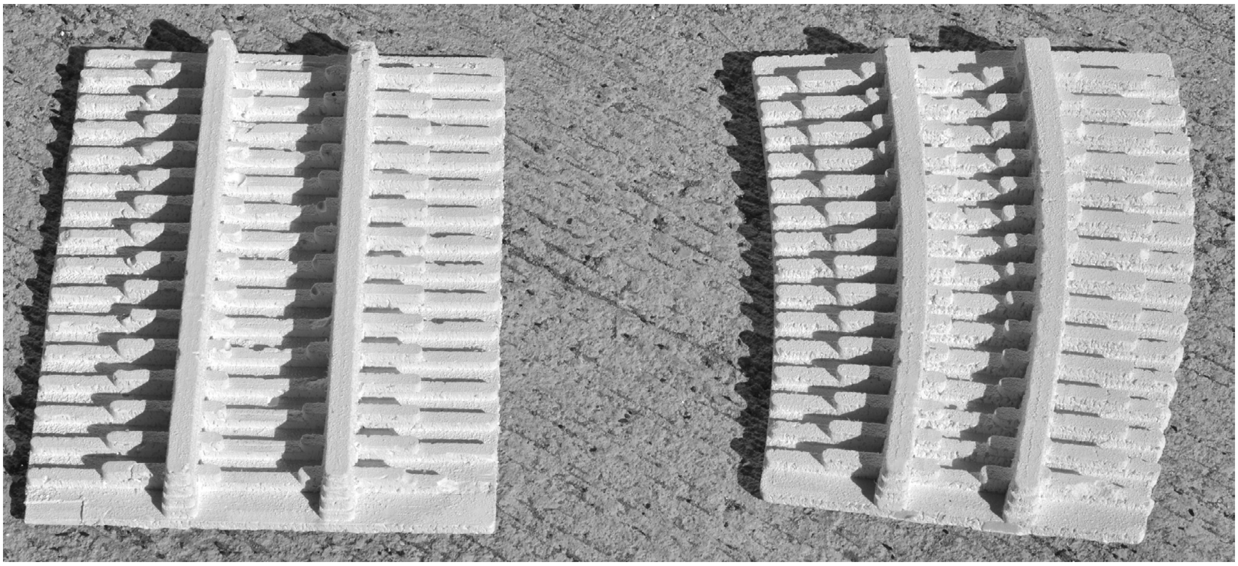

Figure 9: Plaster models of mass-customizable linear and curved roof elements. The tool path is reflected directly in the mould, as it is also defines the shape of the beams.

the geometry translated to tool paths (figure 10) was simulated digitally[3]. The simulation disclosed that a translation into tool paths reduced the milling time by a factor of 3, from 45 to 15 minutes. Further, the simulation showed that milling time was roughly the same regardless of the geometry being curved instead or linear. Two elements were milled and cast to illustrate the principle (figure 9).

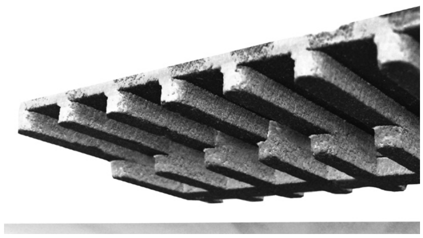

Figure 10: Casting of CNC milled mould

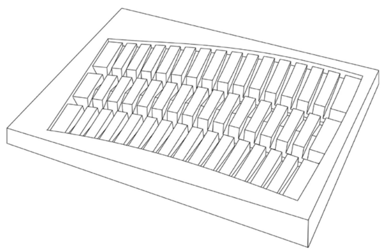

Figure 11: 3D-model of the mould for a bent slab. appx. 200 x 200 mm.

ARCHITECTURAL POTENTIALS

The models made using a table-size CNC miller are potentially translated into a building scale, using industrial CNC routers with a bed size of three

3 The 3D modelling software Rhinocerous ® with the RhinoCAM ® plugin was used for toolpath simulation and gneration or G-code for the CNC router.

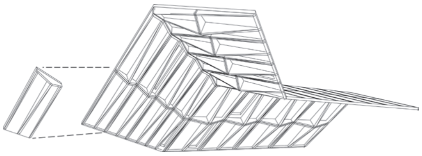

Figure 12: Drawing of a pitched roof made up of 32 individualized concrete elements.

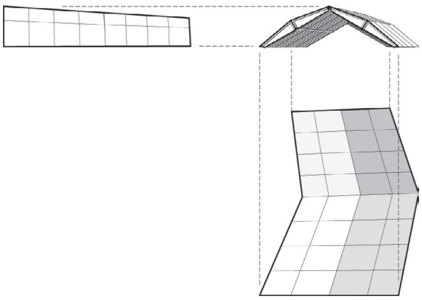

Figure 13: variations in width and height of the overall geometry is possible

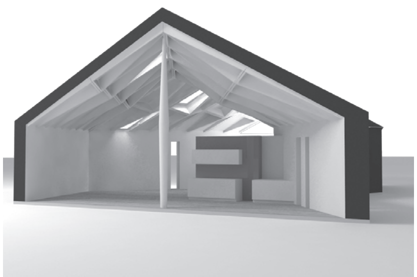

Figure 14: conceptual rendering showing visible beams under the ceiling.

by two meters. Full scale elements, similar in typology to the pre-stressed double-T plates are most commonly used in roof or flooring structures in office and industrial buildings, due to their low weight and ability to cover long spans. The low weight is possible because of the underlying beams, which create stiffness allowing the plate itself to be thin. A special feature of these elements is the composition of both plate and underlying beams in one element. Variations in the geometry, however, are limited to five types of varying width, length and height of the two beams in the element[4]. Creating CNC milled formwork of EPS would result in a greater geometrical flexibility in the entire element, including the beams and for variable height of the beams. This would allow for the production of mass-customised elements, designed to form a more complex overall geometry (figure 12). This is illustrated in an example: a conceptual sketch for a pitched roof, made up of mass-customised concrete elements, designed for a single family house (figures 13 and 14).

The example serves to illustrate how the principle of working with the tool path may be used to create an exposed concrete roof structure, in which the traces from the production are not only visible, but becomes an expressive element as well as a support of the constructive logics in a pitched roof. The shape of the underlying beams illustrates the CNC mill's ability to follow a path of variable depth. But at the same time the changes in the height of the beams illustrate the forces in the roof, which require the largest height of the beam to be in the middle, where deflections are greatest. The architectural potentials could include utilizing the concrete elements to design a building where the changes in size and orientation of the roof throughout the length of the building respond to contextual circumstances, light conditions, flow and views.

Structurally, the ability to skew the overall geometry would increase the stability in the outer walls.

4 The Danish company Spaencom offers five variations: TT30, TT40, TT50, TT60 and TT76

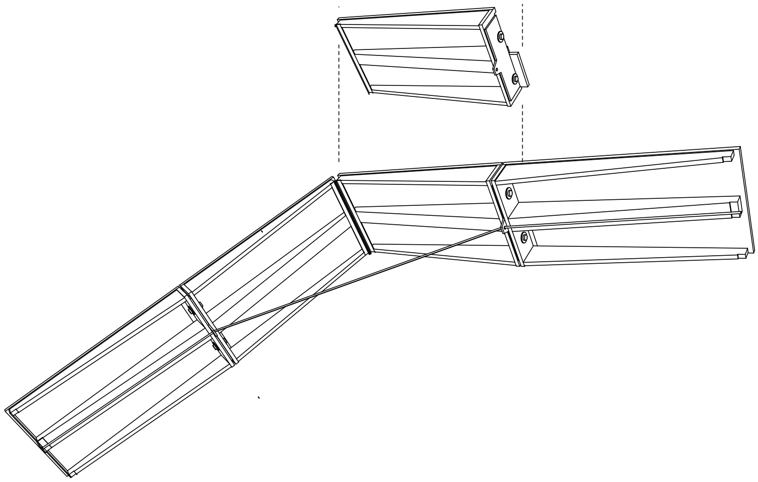

Figure 15: a sketch showing a principle for joining elements by means of metal brackets and tie-rods.

Several aspects need to be addressed to investigate the feasibility of the use of the elements in the way here proposed. The model scale milling needs to be translated into a building scale, using industrial CNC machines with bed sizes of more than two meters. In the case of the pitched roof, a principle for joining could include metal brackets between the elements, which would help adjusting tolerances and provide a fixation point for a collar beam or tension cables to ensure the stability of the roof (figure 15). While the issues of the problematic EPS surface as described in chapter six could be solved by applying a retarder to the mould, it still presents a gap in the relationship between material and technique which is fundamentally unresolved. This will be a focal point in the case study "Under Pressure". Further, the addition of reinforcement is outside the scope of the investigations and would need to be addressed if a full scale element was to be produced.

CONCLUSION

Further development could include a higher degree of parametric modelling, including control over the CNC controller language 'G-code'.

Figure 16: Gatti Wool Factory 1951

Figure 17: A fictional diagram showing the partitioning of land into single family house plots, where each plot is different.

Instead of drawing the tool path, (which becomes the beams), scripting software could be used to evaluate simple 3D representation of the overall geometry of the roof, generating beams of varying positions and depths, depending on the needs for stiffness in various areas of the roof. This would allow for a far more complex network of concrete elements in which the beams are connected, thus adopting some of the structural and aesthetical qualities found in the in-situ cast ceilings made by Pier Luigi Nervi (figure 16).

To speculate on the mass-customised roof for a single family dwelling, the possibility of introducing skewing or bending could be utilised to orientate houses according to contextual circumstances, such as sun orientation, topography, or to maximise privacy (figure 17).

As described in the current use of the technique, the surface is problematic and needs to be treated. In this case a retarder specially developed by Professor Karl Christiansen is used, which prevents the cement in the small crevices between the EPS beads from hardening. The milled EPS blocks would then be transported to a concrete element factory for the application of the retarder, layout of reinforcement and casting. While the resulting surface becomes very homogeneous and thus very three-dimensional and stone-like, the necessity for post treatment is problematic from a tectonic point of view. The surface characteristics appear as a result of solving a problem rather than as a result of the meeting between technique and mould.

CHAPTER 9: UNDER PRESSURE

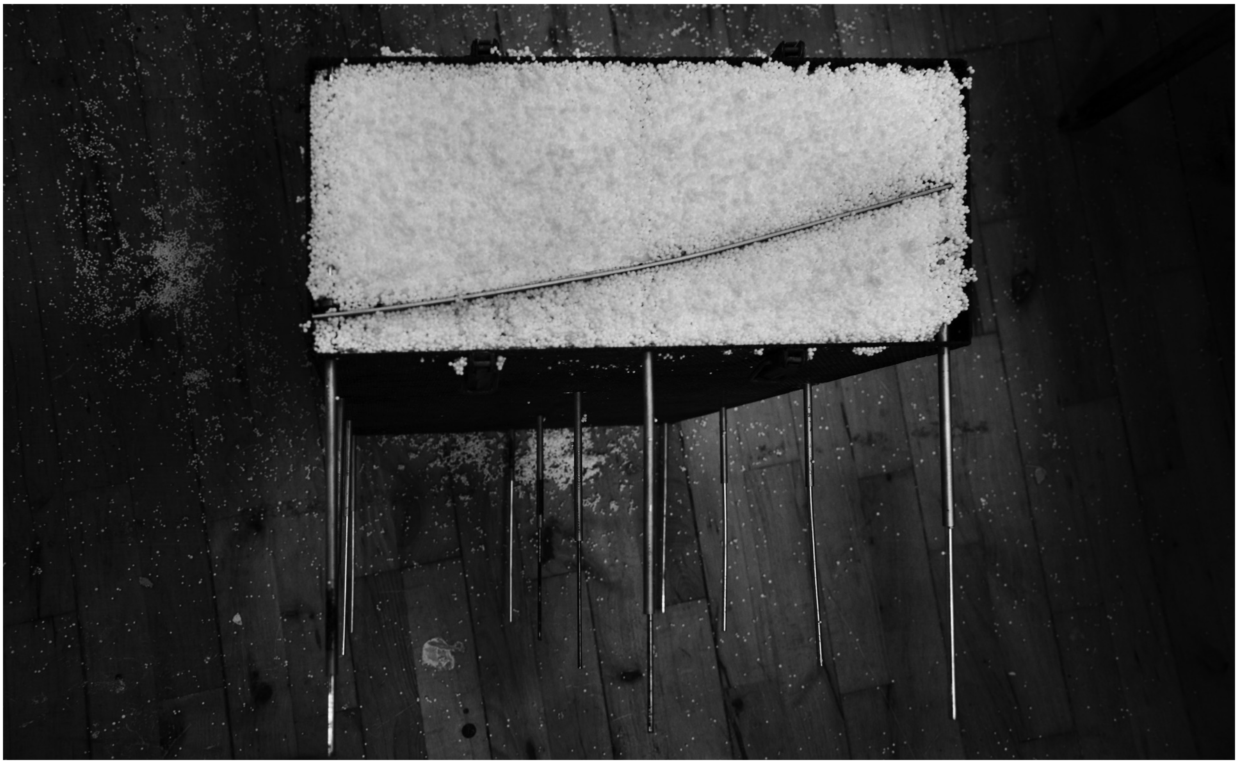

Figure 1: EPS beads to be cast against an adjustable membrane

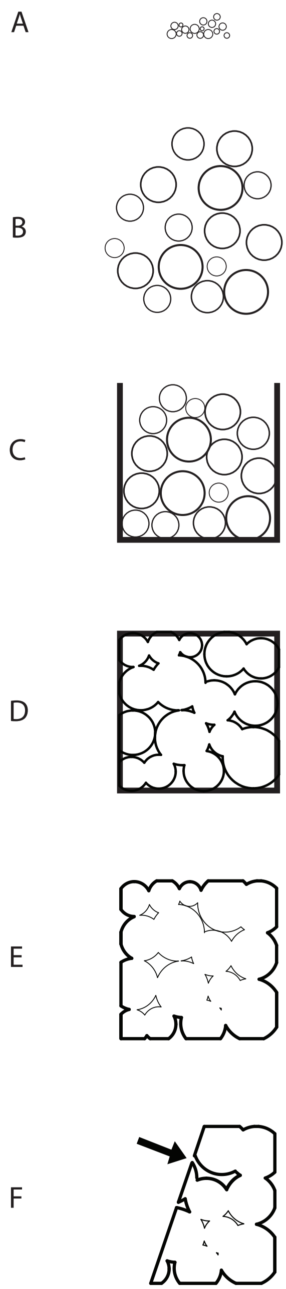

Figure 2: EPS manufacturing process

INTRODUCTION

Under Pressure is similar to the 'Tool Path' case study in that it takes a very specific starting point. This time it is not a technique but a material: EPS. This allows to once again utilise Kenneth Frampton's suggestion that tectonic form originates from *material considerations*. In this case these considerations lead to the development of a *novel casting technique*.

EPS is used in concrete casting where the geometry needs to be complex, as described in chapter six. Moulds are either CNC milled, as investigated in the case study *Tool Path*, or hot-wire cut, as investigated in the case studies *Kofta* and *The Bench*. This investigation takes a starting point in one of the main issues which became evident in these case studies: the fact that the cutting or milling of EPS ruins the surface. To understand exactly why this happens, an account of EPS as a material is needed.

EPS

As the name Expanded Polystyrene implies, EPS is material and a process: namely the *expansion* process. Interestingly, this is quite similar to concrete, which has also been viewed a process, rather than a material[1]. With EPS, as with concrete, it is this process, which is done in three steps, which gives rise to their form.

The first step is the creation of the raw material: beads of polystyrene (figure 2 A). In the creation of the beads, gas is infused into the polystyrene. The beads are very small, under one mm in diameter, and hard as normal plastic. Once produced, the beads are covered with a thin layer of paraffin.

The second step is an expansion process (figure 2 B), in which the gas reacts with the polystyrene. This reaction is initiated by submerging the polystyrene beads in boiling water, causing them to expand to around 40 times their origi-

1 Ref: Adrian Forty artiklen in Liquid Stone

nal size, becoming the lightweight beads visible in the final product. Hence the name expanded polystyrene. The expansion process is timed so that there is still around 6% un-activated gas left in the beads. The paraffin prevents the beads from fusing together, but melts away in the process.

The third step is to pour the expanded beads into a pressure chamber and subject them to steam pressure (figures 2 C and D). This activates the remaining gas, causing the beads to expand more. With the layer of paraffin no longer present, the beads now fuse into the final product: an EPS block (figure 2 E).

The conclusion of this assessment of the process of making EPS is that the material may be seen as an analogue to concrete. Like concrete, EPS consist of innumerable small particles, which are shaped by means of casting against a mould. Due to the high pressure, the beads resting against the mould are compressed, which results in a closed, even surface of the cast EPS block. The inner, porous structure is not compacted as greatly as the perimeter of the block. This is why cavities between beads become exposed when the EPS block is cut or milled (figure 2 F). If concrete is poured directly on top of this inner structure, the weight of the liquid concrete will force cement to seep into these crevices, creating small hooks which make dismantling next to impossible and ultimately ruins the surface. The smooth surface of cast EPS is evident in protective casing for consumer products, coffee cups etc. These objects illustrate that it is possible to cast EPS in complex shapes, which is different from the process of casting EPS for insulation, where the casting chamber is typically rectangular and several meters in width and height[2].
Both productions, however, happen in standardized setups, and the question remains whether it is possible to mass-customize the technique. If cast EPS is to become a mould for concrete casting, a means for controlling the shape

2 In the Danish factory SCA Flamingo, the EPS blocks are up to appx. 3 x 1,5 x 1,5 meters in size.

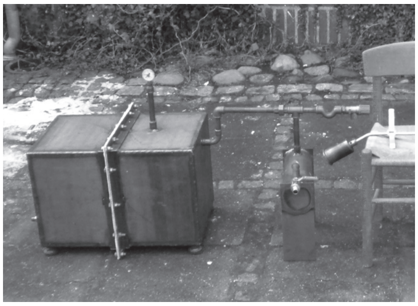

Figure 3: EPS casting chamber with boiler.

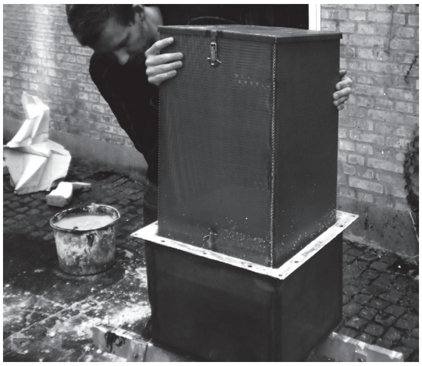

Figure 4: A perforated steel cage retains the EPS beads inside the pressure chamber.

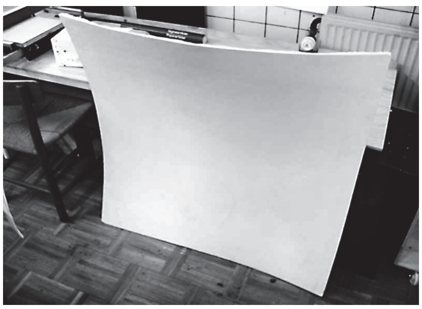

Figure 5: A thin plaster shell used as insert

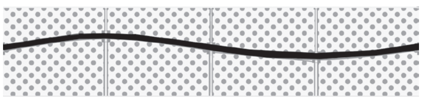

Figure 6: Diagram of EPS beads divided by an insert. Black: the insert, dots: EPS.

within the pressure chamber needs to be devised, allowing mass-customized EPS moulds with a closed surface to be made.

Interestingly, the EPS casting process takes about 10 minutes, allowing for high output rates. This addresses a major issue with the flexible membrane technique proposed by ADAPA, where the concrete needs to cure against the production device, putting it out of service for 12-24 hours. Also, in using this technique the concrete casting is always horizontal. If EPS is cast into the shape needed for the mould, the actual casting may be done vertically, or multiple moulds may be joined to create more complex castings, as elements or cast in place.

THE INVESTIGATION

In order to investigate the feasibility of a mass-customized EPS production, an experiment was planned to re-create the EPS casting process, as described above. For this purpose, a pressure chamber for EPS casting and a steam boiler were designed and built (figure 3).

The chamber was designed to represent the pressure chamber at an existing EPS production facility[3] on a scale of 1:5. Elements cast in the model scale chamber have a dimension of up to 624 x 300 x 120 mm, corresponding to production size blocks with a dimension of 3120 x 1500 x 600 mm.

CASTING EPS WITH AN INSERT

The first experiment investigated whether it is possible to cast EPS with an insert, dividing the EPS blocks into two by a predefined geometry. First, a cage was made to retain the overall shape of the EPS beads (figure 4). Then, a thin shell with double-curved geometry (figure 5)[4] was inserted into the pressure chamber dividing the EPS beads into two blocks (figure 6). The test was a failure because the steam was unable to reach all parts of the mould, creating large areas where the EPS beads had not

3 SCA Flamingo in Skanderborg, Denmark

4 The shell was made with the flexible casting table technique by ADAPA

Figure 7: Failed EPS casting. The plaster insert (visible below the EPS beads on the left) is blocking steam access to the EPS.

fused. This happened because the steam only entered the mould from one source. In industry, a matrix of nozzles ensures an even distribution of steam and a vacuum pump draws steam through the EPS. Also, the three parameters which make the process happen: humidity, pressure, and temperature needs to be tightly controlled. Since these parameters are a guarded industrial secret, the correct mixture is difficult to achieve. Because of the steam coming from a single source, the insert, which was solid, prevented steam distribution with no other sources of steam available to compensate (figures 7 and 8).

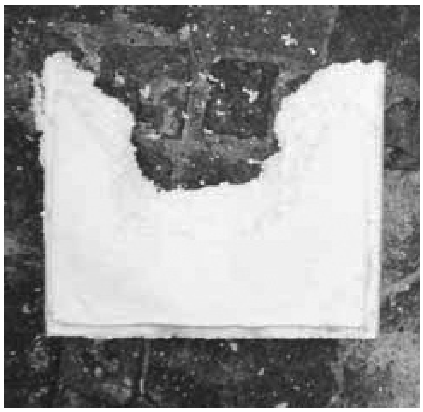

Figure 8: EPS beads fail to fuse if the steam does not reach all parts of the mould.

THE MEMBRANE

Two improvements were made. Inside the chamber, a smaller cage for

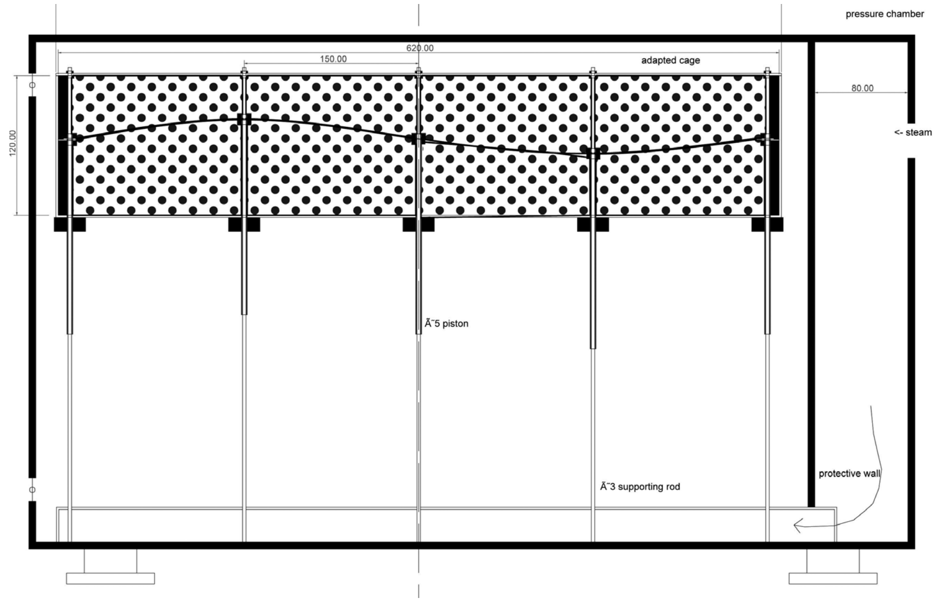

Figure 9: A flexible membrane rig within the pressure chamber. EPS shown as dots.

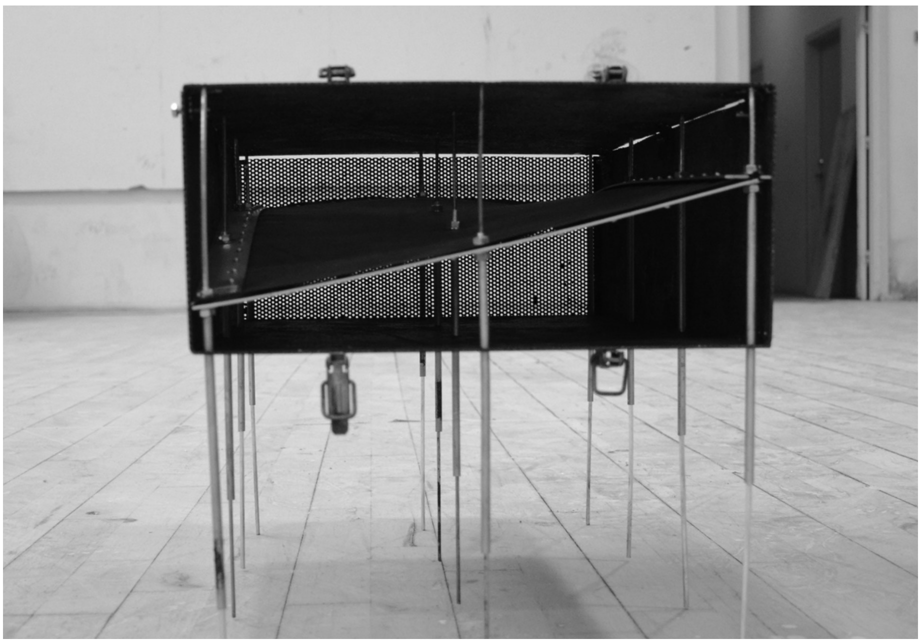

Figure 10: Rubber membrane controlled by a thin aluminium frame and 12 pistons

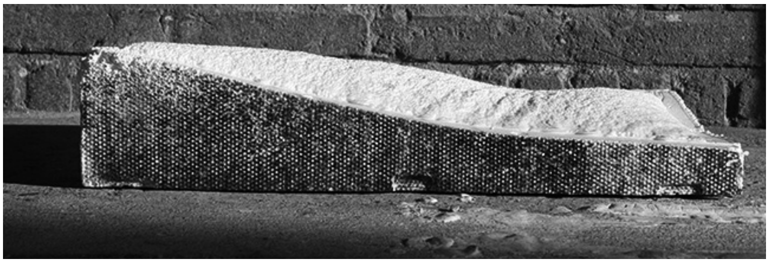

Figure 11: A double-curved EPS block produced in a scale 1:5

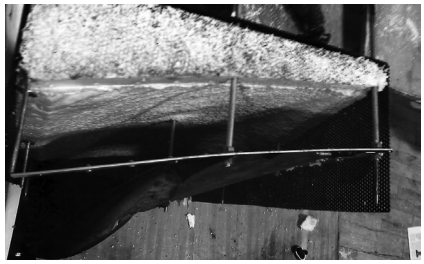

Figure 12: The inner cage after casting. The first half of the EPS is removed.

the EPS beads was made, allowing better steam access. Instead of a solid insert, a flexible, perforated rubber membrane, controlled by 12 push-rods, was designed to enhance steam distribution, while still forcing the EPS to separate into two elements upon casting (figure 9). The push-rods were controllable, allowing alterations to the membrane. An aluminium frame was added to precisely control edge conditions (figure 10).

The alterations to the pressure chamber improved the result significantly and it was possible to cast a double-curved EPS block (figures 11 -13) and a concrete element (figure 14). The EPS farthest from the source of steam, however, still suffered from insufficient steam pressure, resulting in one EPS block being complete and one being only partly cast.

The primary potentials of the technique: the casting in a two-sided EPS mould requires the two EPS moulds being placed with a gap between, into an outer retaining box and concrete poured to create an amorphous concrete element, demonstrating curvature on both sides of the element. Trial-and-error experiment leading to better steam control and a thicker membrane finally resulted in a successful two-sided EPS casting, and subsequent concrete casting (figures 16-19). The concrete was cast directly against the EPS without any treatment of the surface. After curing,

Figure 13: EPS mould removed from pressure chamber

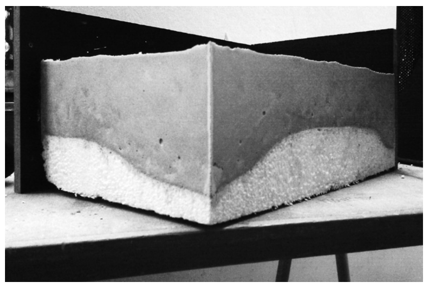

Figure 14: Concrete casting against a double-curved cast block of EPS

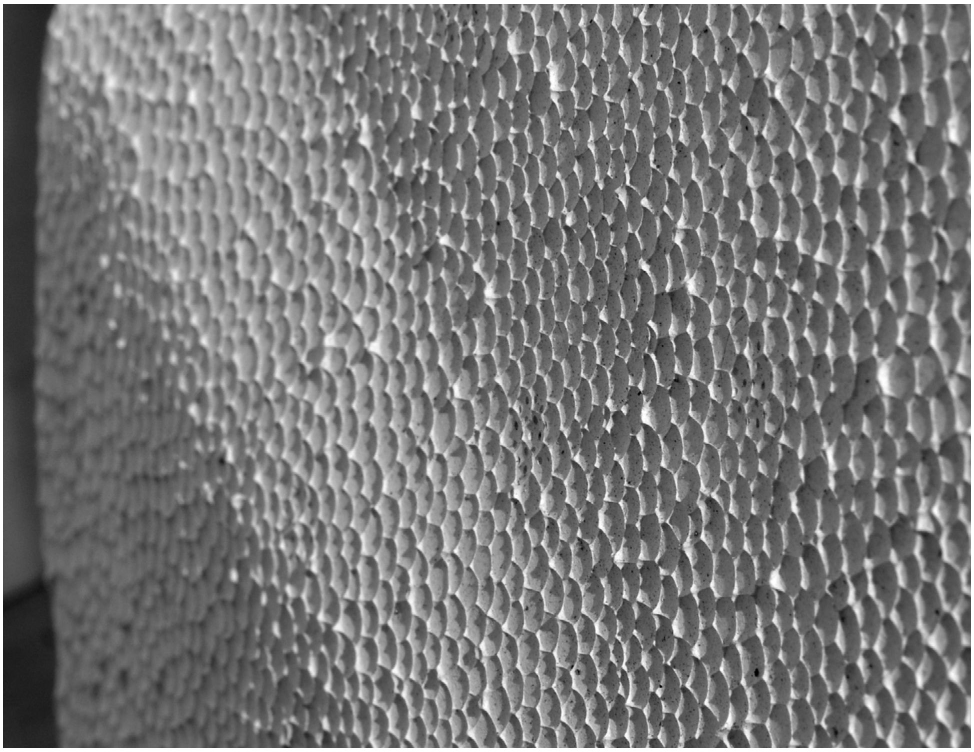

Figure 15: The surface of concrete cast against industrially made, closed surface EPS. An EPS wrapping for a TV set was used to examine the surface qualities.

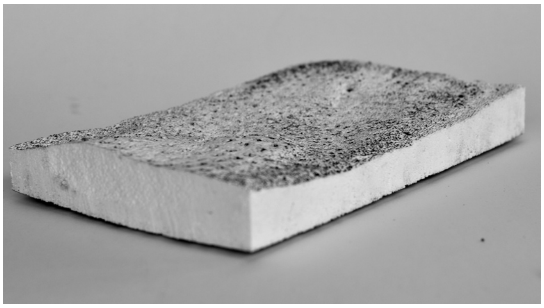

Figure 16: Mould with marks from the rubber membrane

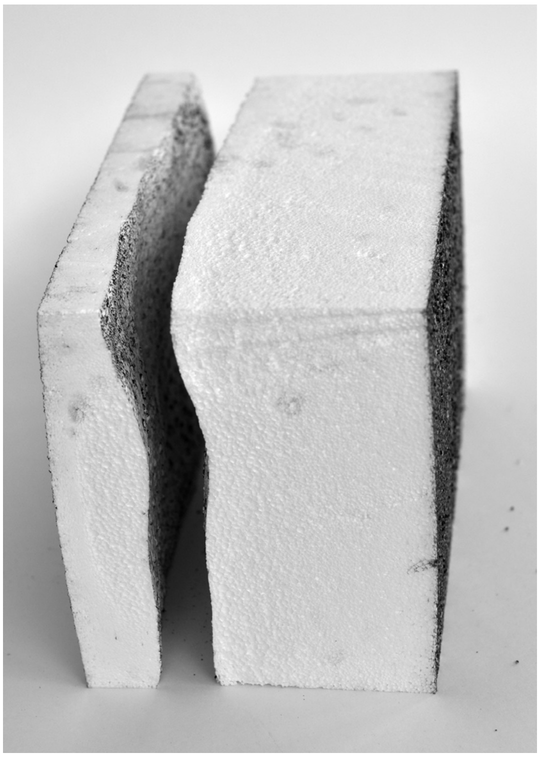

Figure 17: Cacst EPS, split a rubber membrane

Figure 18: Negative volume in which concrete is poured.

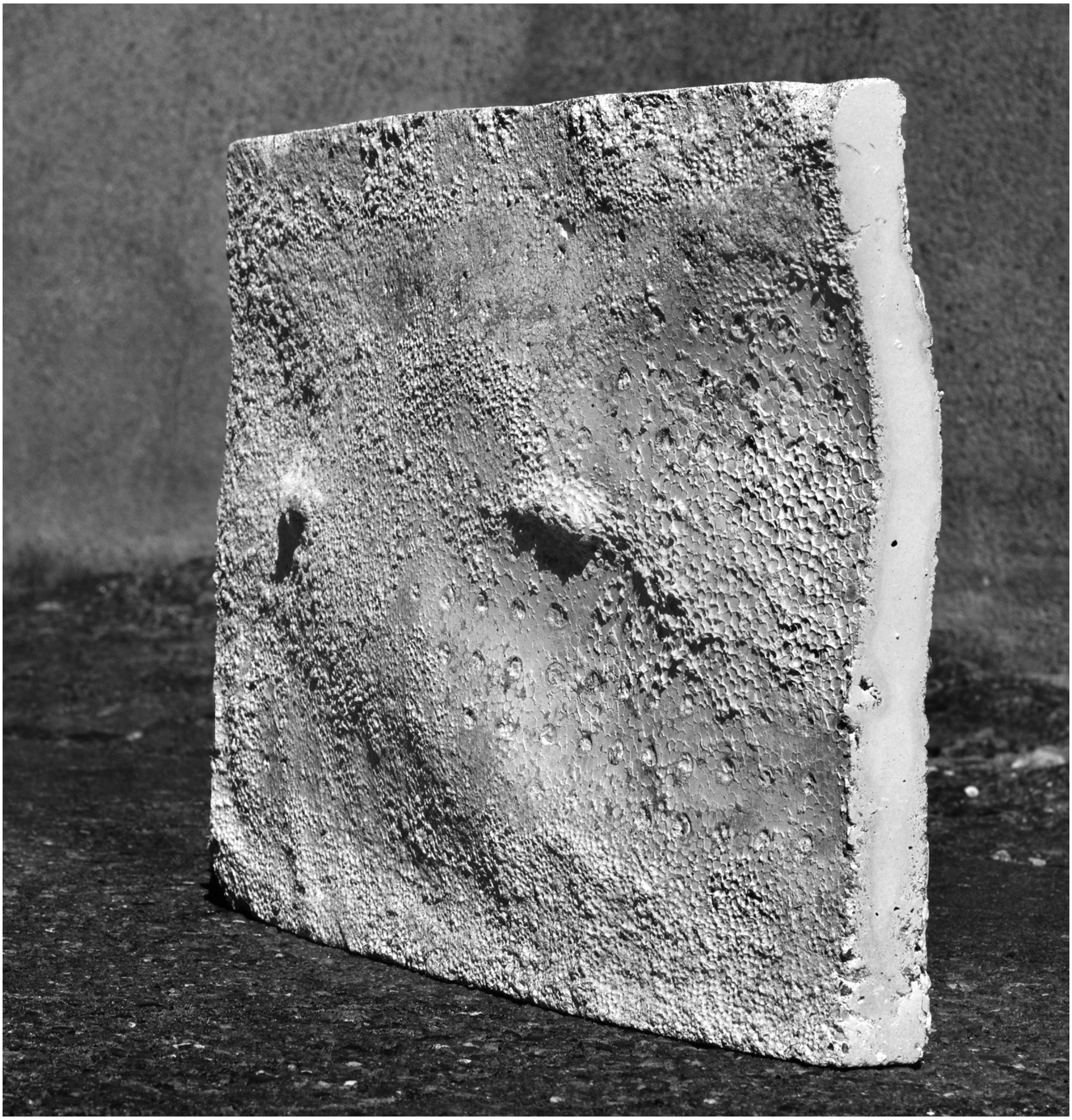

Figure 19: Concrete element cast against EPS. The EPS was cast under steam pressure against an adjustable membrane

the EPS released with only minor release problems and the surface was closed. Differences in steam pressure, did cause an uneaven surface not nearly as perfect at could be achieved with industrially cast EPS, exemplified with a concrete casting test against the complex shaped EPS wrapping for a TV set (figure 15).

CONCLUSION

The case study allowed for amorphous EPS casting moulds to be made without ruining the surface. This eliminated the need to expose the inner structure and resulted in a high surface quality. The EPS surface is rugged, but remains closed, and concrete cast against this surface resembles that of a golf ball, as the convex beads transform to concave imprints. This gives the surface a subtle, uniform texture and a play of light and shadow, which records features in the making of the mould, a record which is lost when casting against hotwire cut or CNC milled EPS, because it needs to be covered with either a plastic film, a rubber membrane or with retarder.

The casting technique illustrates that amorphous concrete elements may be produced quickly, which is an advantage when compared to CNC milling or the flexible casting table technique.

One may also conclude that the controlling the temperature, pressure and humidity needed to ensure proper fusion of the EPS bead is difficult to achieve. A satisfactory quality of EPS requires an industrial setup, where steam is better distributed through the EPS. Due to the difficulty of getting both sides of the membrane to fuse properly, it was not possible to advance to experimentation with controlled piston positions (figures 20 and 21), measuring of tolerances and the possibility of casting larger

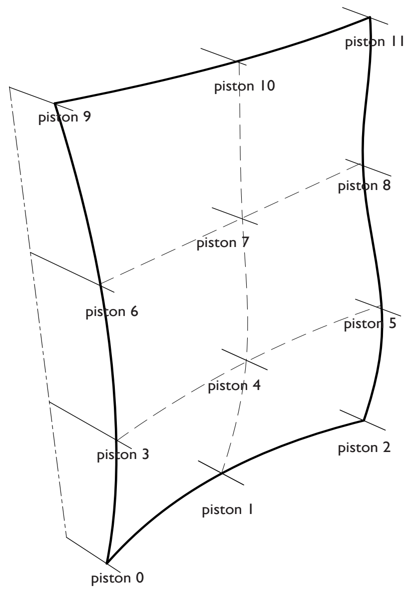

Figure 20: future research would include the development of a means to easily set and fixate the pistons.

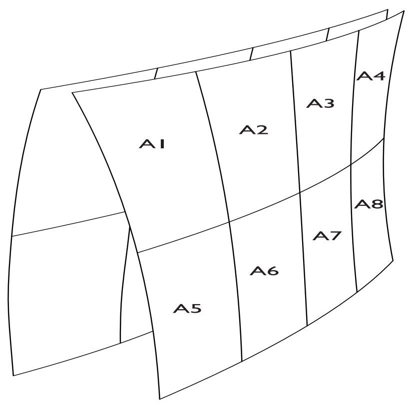

Figure 21: A diagram showing how curved concrete elements blend the traditional shift from wall to roof


Figure 23: Meiso-no-mori Crematorium, external view

concrete elements in a compound of EPS moulds. As such, the results of the pressure chamber experiments are of limited use in an assessment of the architectural potentials of the technique, but the experiment is illustrative in explaining how tectonic evaluation of a material may give rise to new use of technology. Through an evaluation of the tectonic implication of using EPS, the cause of existing obstacles in the use of EPS for concrete casting was identified, which initiated the development of a new technique. Controllability of the mould geometry was sustained while two improvements over existing EPS casting techniques were achieved: a shorter manufacturing cycle and an answer to the surface problem.

Further experimentation should take place in co-operation with the industry, in order to utilize the knowledge regarding the physics of EPS casting, to up-scale the experiment to a building scale and to further develop the flexible membrane.


Figure 22: Meiso-no-mori Crematorium, interior view.

ARCHITECTURAL POTENTIALS

Figure 24: Visualization of a wall of double-curved concrete elements.

The Meiso-no-mori Crematorium in Japan by architect Toyo Ito may serve to illustrate the architectural potentials of double-curved concrete in architecture. Here, the concrete roof creates a spacious and lightweight feeling internally, while entering an abstract dialogue with the surroundings (figures 22 and 23). In this example the concrete is only carrying its own weight, but the ability to cast thicker, load-bearing concrete elements would allow the construction of load bearing outer and inner walls, which also become the roof. In such cases an assembly of elements would be appropriate, using the same techniques which have been developed for assembling rectilinear concrete elements (figure 24).

CHAPTER 10: HELLO WORLD

Figure 1: The Hello World sculpture

INTRODUCTION

As described in chapter six, recent work at the University of Manitoba by Mark West and others has seen experimentation into the use of precast concrete elements, using flexible formwork and allowing gravity and hydrostatic pressure to generate form. The case study draws inspiration from the textile casting technique, but differs from West et. al.'s approach in that it uses more rigid, foldable moulds to cast smaller planar elements where the overall curvature of the system is a consequence of angled joints. As such the topic is the *development of a novel technique*. The case study also builds on Marco Frascari's concept of the *details as a creator of meaning*. That is: details around the act of transformation of a material and the details which arise, are key to the progression of the case study.

The major potential of casting in textile is the fact that a lot of form is achieved using very little technology. As described in chapter six, this was found to be a consequence of the technique utilizing *deformation* as an overall method. However, the lack of resistance to anything but tension in the textiles was found to cause a lack of control over geometry.

The case investigates deformation that can be used to generate casting moulds with a complex geometry, while enhancing the degree of control over the concrete castings. In the *Under Pressure* case study, the proposed technology proved difficult to control. Drawing from this conclusion, a technology was chosen which is simple and accessible for the moulds to be successful, while allowing for mass-customization: laser cutting. Laser cutting also allows for digital control, allowing investigations into the concept of *digital tectonics*.

These topics may be summed up as two areas of investigation, which were used to govern the case study:

The *first area of investigation* aimed to locate a material and a technique which would allow for a predominantly deformative method of generating the casting moulds, but with a greater degree of control.

The *second area of investigation* was to establish a method for generating and describing complex casting moulds, built to match the transformational technique and the chosen technology. This idea of *modelling* as described in chapter three was introduced as the method to achieve both control and complexity. Specifically, digital modelling was used to describe both material and technological preconditions in the generation of a structure consisting of concrete columns and beams.

MATERIAL CONSIDERATIONS

To address the material, the act of transformation was considered. As described in chapter six deformation, a subset of transformation has been successfully used to create textile casting moulds. The deformation happens by the material bulging and stretching, which is hard to control. A different act of transformation, which is easier to predict, is *folding*. Folding is possible if a material has a molecular structure which is permanently changed after the fold is made, but is sufficiently flexible in molecular structure to retain its strength in the fold line without becoming brittle. Further, the material needs to be thin enough in order that a low force causes the material to deform.

Since the moulds would all be unique and therefore not reusable, a materially efficient and low or zero-waste production method was desired.

FOLDABLE PLASTICS

The above described properties were found in plastic. To find the plastic type best suited for folding, the properties of four types of plastic was examined: PETG, PE, Acrylic and PVC. Parameters included the brittleness and memory-effect of various types of commonly used plastics (figure 2). Best performance was found in PETG plastic, which is part of the PET plastic family. According to 'The Injection Molding Handbook'[1] it is eas-

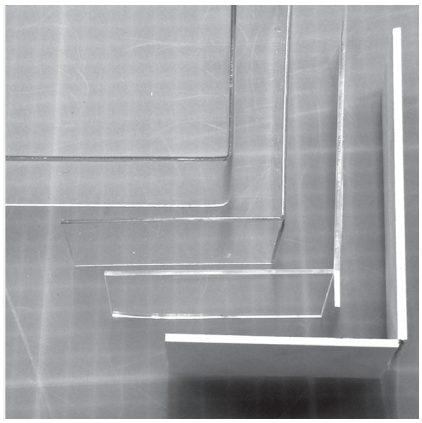

Figure 2: Foldability test of four standard plastic types. From top to bottom: PETG, PE, Acrylic, and PVC. PETG proved a suitable mateial for folding, as is was ductile while the other three were brittle .

1 Dominick Vincent Rosato, Donald Vincent Rosato and Marlene G. Rosato, Injection Molding Handbook (Springer, 2000) p. 574.

Figure 3: PETG mould bend into shape following crease lines.

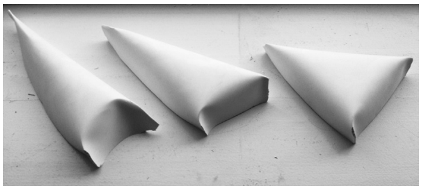

Figure 4: Plaster models investigating minimal-effort moulds.

ily recycled, by melting, at between 193 and 274 ºC, evaporating only CO_2 and water and its molecular structure allows for infinite use and re-use without degradation if it is kept in a closed recycling process. In terms of the design theory Cradle to Cradle[2], the PETG is used as Technical Nutrient, in a zero-waste production. Importantly it does this while adhering to the basic requirements of being easy to fold and offering a high quality mould surface. The plastic sheet comes covered with a thin protective film, used to protect the material against scratches during transport. This film was left on during casting and then removed to leave a clean sheet ready for recycling.

PETG can be hand-folded without any preparation of the material, but this is hard to control. The addition of dashed crease lines, however, was found to enhance precision and reduce the amount of material which needs to be forced into folding (figure 3).

Based on the initial investigations and the conclusion from this material investigation, a technology was chosen which allows for the manipulation of PETG plastic. Laser cutting was found to be suitable for three reasons. It offers high speed cutting rates; it is digitally controlled, thus suitable for mass-customisation; and it is accessible and requires no modification in order to be able to cut PETG plastic.

GEOMETRY AND CASTING PRINCIPLE

A series of simple physical models were cast in order to examine how a minimum of folding may produce complex geometry (figures 4 and 5). It was concluded that the radii and exact location of soft edges were hard to govern (figure 5) while the most controllable geometry was one where all changes in direction in the geometry are defined by a sharp edge. Put differently, all edges should be linear and have a near-zero radius. Even

2 William McDonough and Michael Braungart, Cradle to Cradle: Remaking the Way We Make Things (Farrar, Straus and Giroux, 2010)

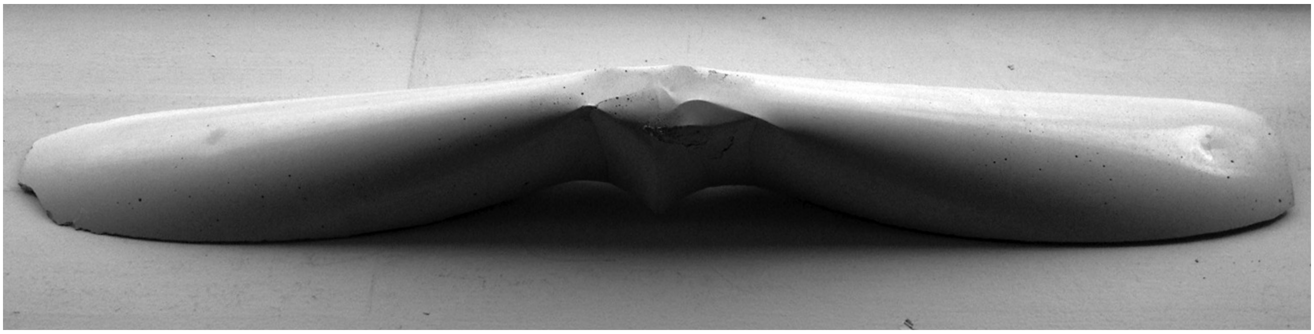

Figure 5: Concrete scale model of an optimised beam cast in folded PETG plastic

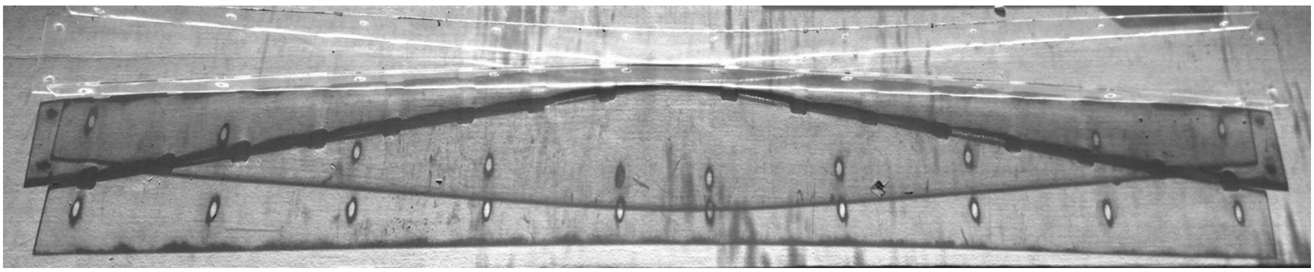

Figure 6: Complex geometry is achieved with two folds.

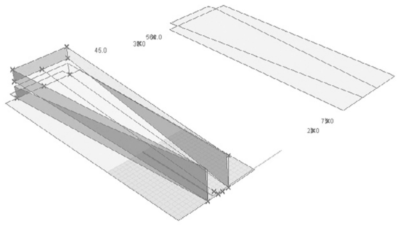

Figure 7: Parametric model of an optimised beam with embedded logics for un-rolling.

though this gives the concrete element a less amorphous look, it is still possible to get a lot of form using little technology, in that a many-faceted concrete element can be produced making a few folds (figure 6).

DIGITAL MODELS

In order to incorporate the concept of modelling, a script was made which defined both the geometry of the concrete element and the unfolded template for laser cutting (figure 7). This script was used to produce and cast a series of model scale concrete beams (figure 8). The tests confirmed that the template was precise, and that mass-customised concrete members could be manufactured from the same script. The test also disclosed a deformation in the moulds when exposed to the fluid concrete. It was necessary to perform stress and deformation simulations as part of the development of components, in order to check that the PETG could withstand the weight and hydrostatic pressure from liquid concrete (Figure

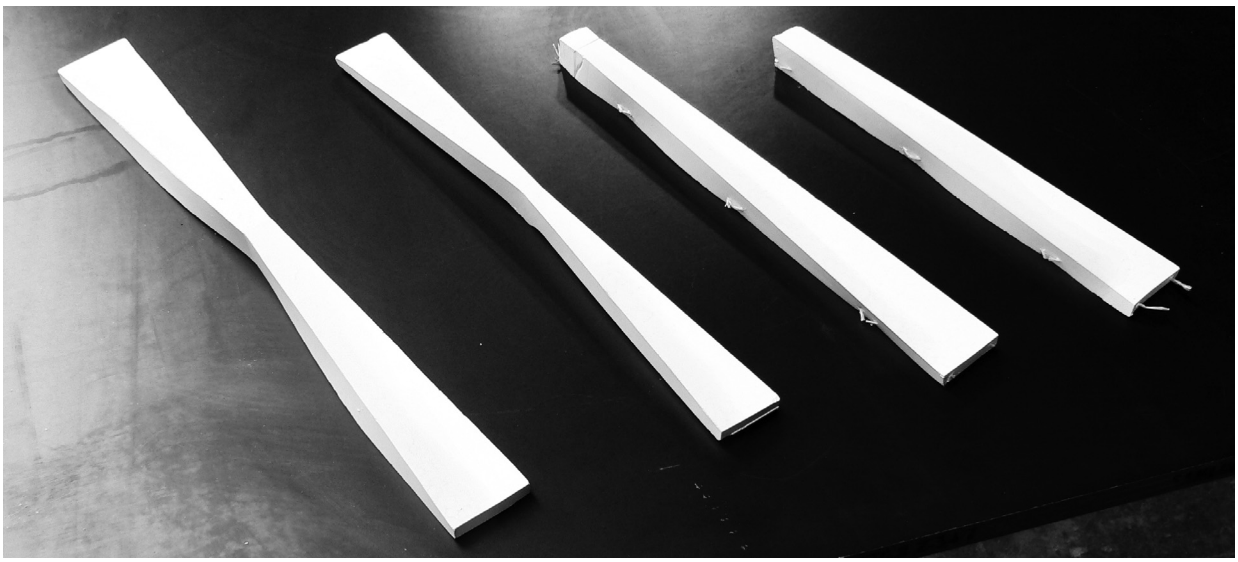

Figure 8: Scale models of parametrically defined, folded beams

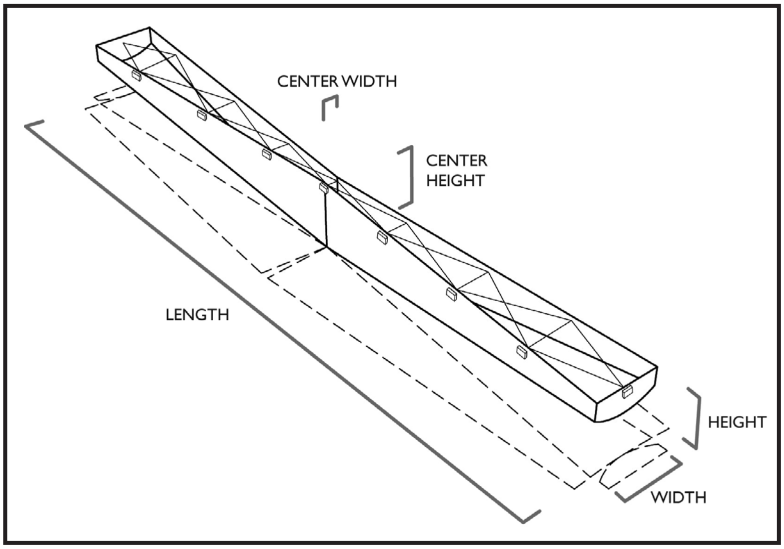

Figure 10: Variables in a beam embedded into the parametric model

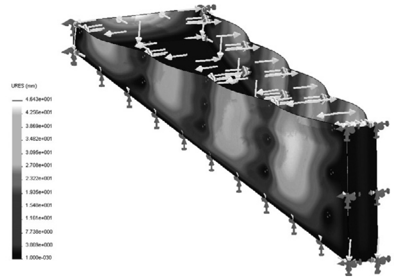

Figure 9: SolidWorks® displacement analysis of a concrete beam cast in 1mm PETG.

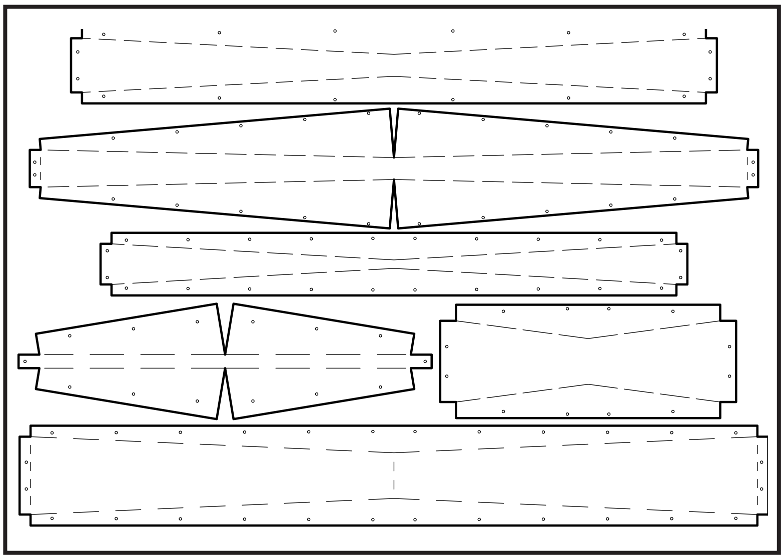

Figure 12: Laser cutting template for six different columns made from the same parametric model.

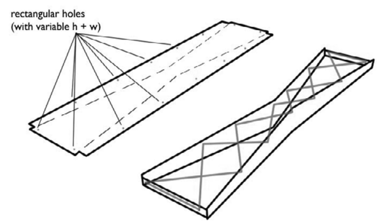

Figure 11: A system of bracing the sides of the mould, which doubles as reinforcement

Figure 13: Parametrically defined concrete beam in scale 1:2 (length: 1200mm), cast in laser-cut PETG plastic. A cross-connecting tie has failed, causing excessive deformation at one of the nodes.

Figure 14 : Full scale test: A parametrically defined, reinforced concrete beam with a length of two meters.

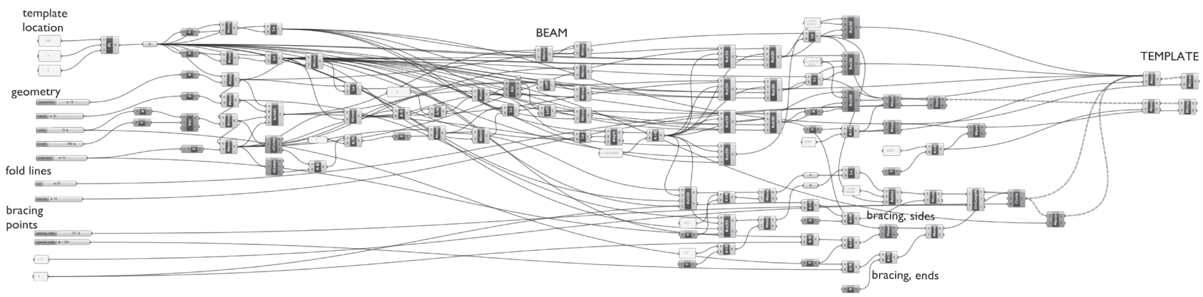

Figure 15: Script performing component generation, placement, and template unroll.

9). The script was refined to allow for variable width, length, height, as well as centre width and height (figure 10). Bracing of the moulds against these forces was also included (figure 11). The digital models were tested in a scale 1:2 (figures 12-14).

THE HELLO WORLD STRUCTURE

The ability to parametrically define a structure and its individual members was investigated in the sculpture "Hello World". Based on the findings from the material and digital experiments, a script was written (figure 15). The script did three things:

Firstly, a method to read an input was defined. In this case, polylines, corresponding to the centerline of the members in the sculpture, was used (figure 16).

Secondly, the polylines were coupled to the functions which generated the geometry for each member (figure 17).

Thirdly, an unroll-function was defined, which read the parameters of each object and generated flat sheets for laser cutting (figures 18 and 19).

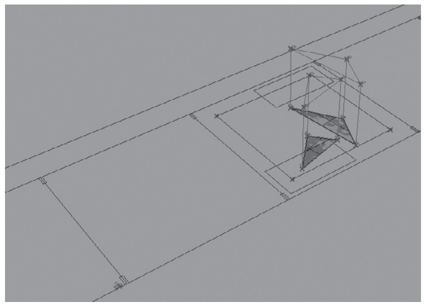

Figure 16: Polylines defining the centre of columns and beams

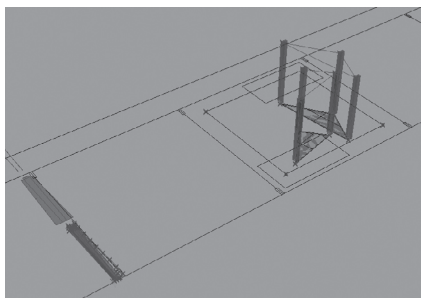

Figure 17: Geometry is created and unrolled for manufacturing

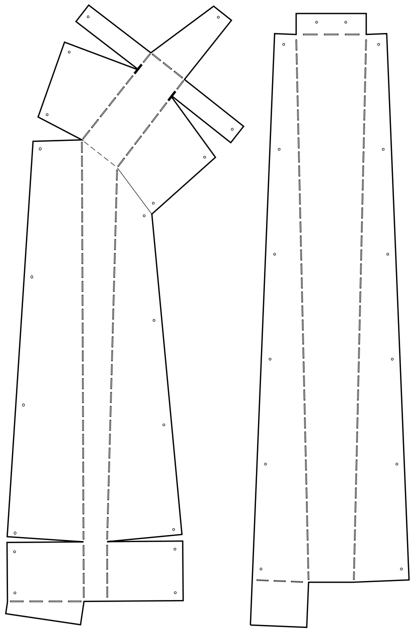

Figure 18: scaled drawing of an un-rolled geometry for a two meters long concrete beam.

Figure 19: laser-cut template with blue protective film covering the PETG.

SCRIPT REFINEMENT

The arrangement linear arrangement of the script as input-geometry-output is called procedural coding, and becomes difficult to overlook once the script grows in complexity. This problem is also known as 'spaghetti-code'[3]. It is hard to read and thus hard to alter and improve the script.

The parametric model, however, greatly improves the physical models – allowing for precise moulds and the investigation of a number of variations that would have been hard to make up in analogue models. This, in turn, allows for more complex form-generation, where the inherent possibilities for cutting and bending the material are utilised.

To deal with the lack of transparency in the code, the script was altered on the basis of the object-oriented programming paradigm. The Object Oriented Paradigm is described in the book 'Elements of Parametric Design' by Robert Woodbury4 In this approach, parametric modelling is seen as the sketching of several objects simultaneously and the grouping of objects with similarities or connections in a class. The idea originates from computer programming; software code can grow too complex to grasp when written in a linear manner, but becomes or is intuitive, transparent and flexible when structured as objects and classes. This included the definition of classes, which are blueprints, from which innumerable instances can be made, called objects. Transparency is enhanced adding by visual strategies for the structuring of code, as described in the paper 'A Visual Formalism for Objectoriented Design'[5]

Because of this distinction between the actual geometry (the object) and the method by which it is defined (the class), the script could be arranged so that a few standardised blocks of code (the classes) could be used to generate multiple members (the objects). These objects in turn invoked instances of an unroll class, creating all of the unrolled geometry (figure

3 Reverend Bill Blunden, Software Exorcism (Apress, 2012), p. 123.

4 Woodbury, Robert. Elements of Parametric Design. 1st ed. Routledge, 2010, p185-274

5 Amnon H. Eden, A Visual Formalism for Objectoriented Design, in Integrated Design and Process Technology, IDPT-2002

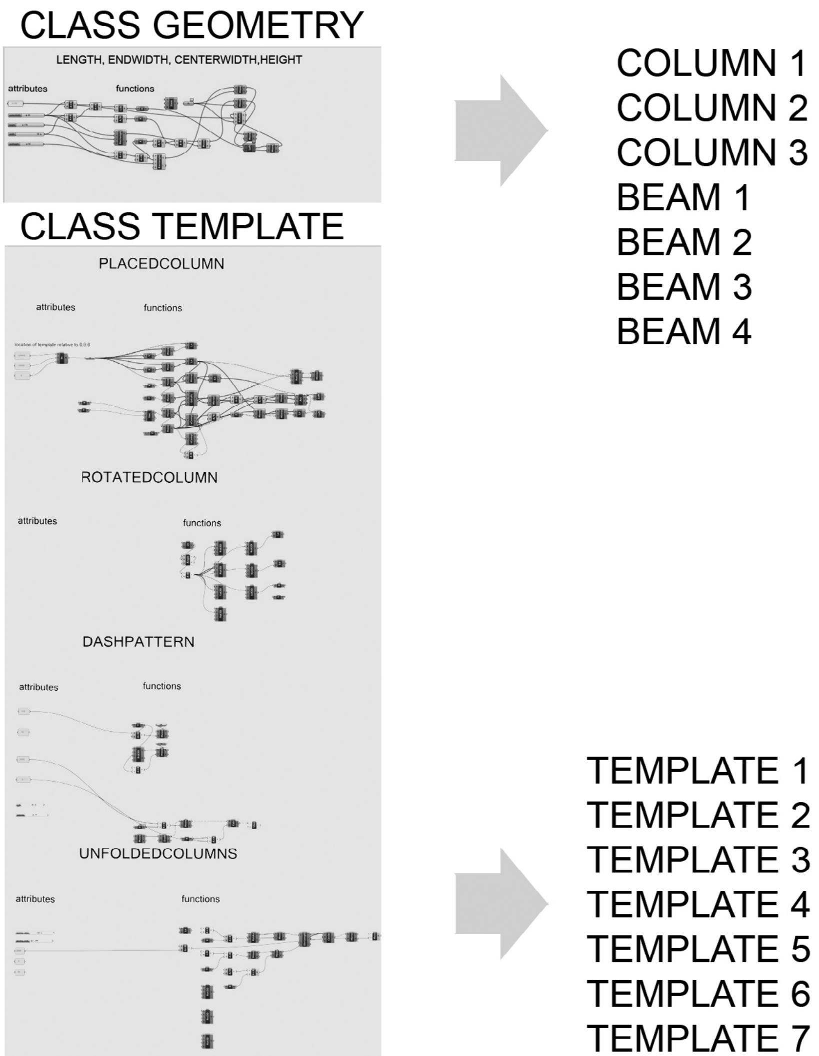

Figure 20: Arrangement of Grasshopper® code in two classes, instantiated into seven objects.

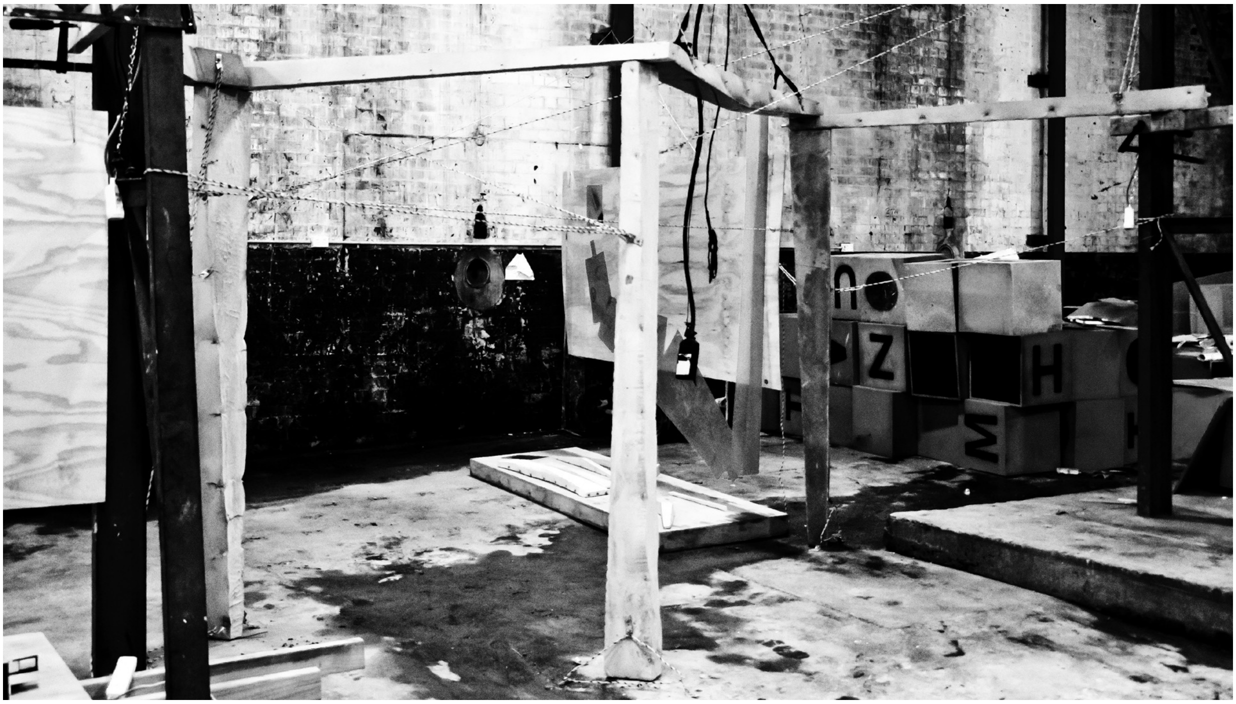

Figure 21: The ‘Hello World’ Structure

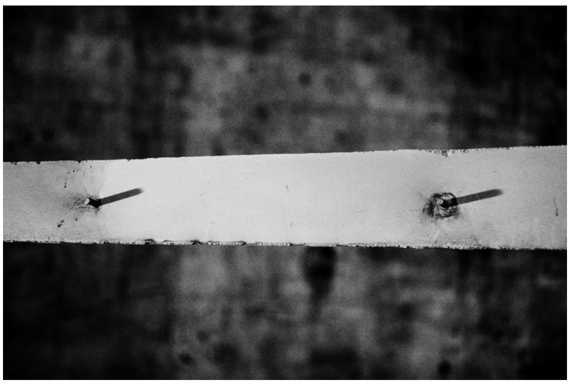

Figure 22: detail of a concrete beam

Figure 23: The bracings left in the concrete tell a story about the making of the element.

Figure 24: One of three mass-customised beams.

Figure 25: Concrete element surface shine.

Figure 26: Deformations of the mould are visible in the concrete element.

20). Through these alterations, it was possible to overlook the whole script and make adjustments to both placement and geometry of the concrete elements, allowing the casting of seven individualised concrete members, four beams and three columns (figures 21 -27). Measurements taken from the cast members showed that tolerances across the folded edges was under 2 mm, while deformations of the open sides of the moulds, where the the mould sides were braced with tension wires, were significant and required analysis to stay within limits (figure 26).

ANALYSIS

The introduction of digital form-generation in the experiment gives rise to two circumstances, which needs to be considered: First, digital form-generation, when done with respect to the technique, should encourage exploration rather than just replicating physical models or obvious manufacturing logics.
Second, and as a consequence of the complexity which follows the first circumstance, an iterative design process is required. The object oriented programming paradigm was found to be a help in dealing with this complexity.

DIGITAL EXPLORATIONS BASED ON TECHNIQUE

It is challenging to use parametric models in a way which encourages exploration and does not limit it. This is particularly true in digital modelling where material and technological evidence, rather than a computational logic, is the starting point. The problem arises when the focus is turned towards trying to get the parametric model to express a 100% true replica of a physical model, as this imposes serious limitations on the exploration of form. Also, with the code arranged in procedural manner, it is easy to see the code as a linear process moving from A towards the final goal B. With all efforts geared towards perfecting the final goal, it is hard to grasp all of the steps between A and B, which may be relevant points for exploration in many directions – the casting technique, the geometry, or the arrangement of elements in a series of architectural concepts.

When parametric modelling is initiated as a tool for generating manufacturing output, it is easy to miss its potential to function as an explorative tool. Development is focused on elements rather than systems, members rather than a construction. Instead, use of parametric modelling in the early stage of sketching should boost a generative approach to quick investigations of the many possible developments and uses of a system. As such, it should have a simplicity that allows for quick alterations, the addition of new geometry or new relations between existing geometric shapes – at all times keeping the material, technology and casting technique in mind. In other words, what is needed is an abstract and general parametric model based on overall conclusions from the physical models, which can function as a test bed for numerous concepts, which is what parametric models do well.

OBJECT ORIENTED DESIGN: AN ITERATIVE PROCESS

Splitting the parametric model into classes and objects is strategy more familiar to software developers than architects and designers. The division is purely organizational, meaning it can be implemented as a certain way of arranging and connecting the elements in the digital design tools.

An experiment with dividing the script into three classes of concept, manufacturing and geometry has proved practical (figure 27). As opposed to starting with one of the three and then moving on one step at a time, all are defined and developed simultaneously. In this experiment the division helped the exploration of material, structural and contextual influences on the form. With regard to material, it helped refining the crease lines, which improved the technique and became visible in the cast concrete (figure 28). With regard to structure, it helped identify the information needed to test material stress and deformation by creating an external 'object' in Solid Works®, linked to Grasshopper® with Excel® as the mediator. With regard to the concept it allowed for quick

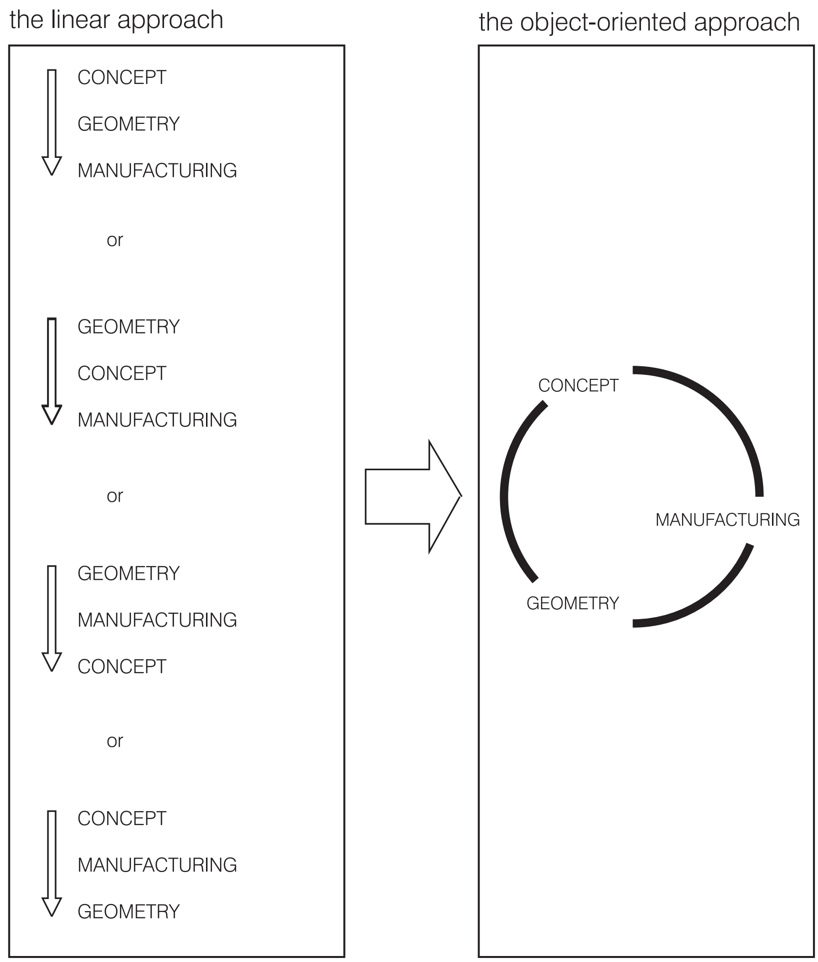

Figure 27: The linear versus the object oriented approach

tests of multiple organisations for the placements of columns and beams in a sculpture. In other, more complex projects these influences could involve considerations regarding function, logic of assembly, and material optimisations.

CONCLUSION

"Hello World" shows that parametric models can support the generation of concrete structures which can respond to complex material, conceptual and contextual relations. Abstract parametric concept models that are qualified by material properties or a specific casting technique can work as a powerful tool for exploring several concepts which are all part of a tectonic logic.

The parametric models are seen as a tool which enables a generative process, exploring boundaries rather than defining solutions. The parameters qualify the design in a way that can have a direct influence on architectural control. As such, the proposed method for combining materials and technology with parametric modelling involves the use of parametric modelling as an explorative tool. Material and technological investigations form the basis for the digital model which prevents the generation of arbitrary, digital representations which would translate into complicated and expensive manufacturing techniques. The method involves a structuring of the script in classes and objects in order to keep track of the possible points of interference and development[6].

It was concluded that parametrically defined concrete elements cast using the applied technique can be both complex and accurate. Due to the deformations on a sub-component level in the large concrete components, it was decided that further experiments should be focused around smaller concrete components.

Figure 28: The crease lines are visible in the concrete, giving a hint as to the nature of the mould.

6 The experiment in this case study and the considerations regarding the object oriented approach are elaborated in the paper: Pedersen, O. E. Material Evidence In A Digital Context: Exploring the tectonics potentials of concrete. In Svaneklink, A. (Ed.), Context 1010 / 2011. (pp. 14-15). Aarhus. (Aarhus Documents; No. 2, Vol. 1, 2012).

CHAPTER 11: REVAULT

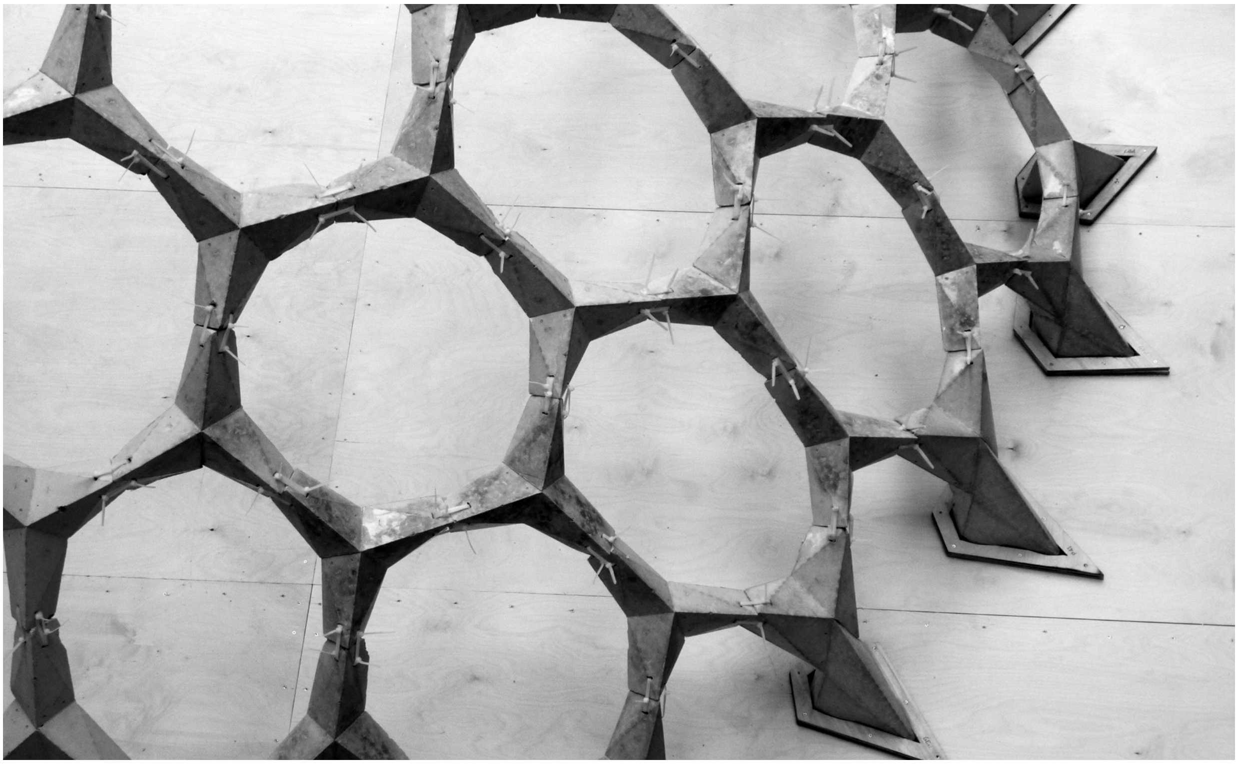

Figure 1: The ReVault Pavilion

INTRODUCTION

The aim of the 'ReVault' case study was to gather previous findings regarding *digital tectonics, poetics of construction, the details as signifier*, and the idea of a *New Production Philosophy,* including *mass-customization, Cradle to Cradle,* and *resource optimisation*.

The goal was the design and construction of a pavilion (figure 1), making use of the technique developed in the 'Hello World' cast study, while addressing the issue of deformation in the large concrete elements.

The case study was completed in collaboration with architects Dave Pigram and Niels Martin Larsen, who specialise in digitally based generative techniques and computation. Besides the researchers and consultants, a group consisting of students from both Aarhus School of Architecture and the University of Technology, Sydney, participated in the development and realization of the pavilion.

Laser cutting and folding was further developed as a means of creating the formwork and the complexity was increased in that the generation of both the overall form and the concrete components was done digitally.[1] In other words, the focus was the construction of a digitally defined concrete structure from small-scale individualized elements, cast in PETG plastic.

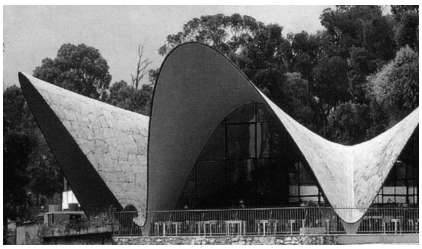

Figure 2: Compression-only concrete shell for a restaurant in Xochimilco, Mexico by Felix Candela.

This investigation is used to assess a design method of complex concrete structures, which may be described as an iterative process, negotiating both physical and digital constraints[2]. This involves consideration of the relations between geometry and technique, as well as the use of form-finding and simulation algorithms for shaping and optimizing the shape of the structure.

1 In the 'Hello World' case study, the overall form was not defined digitally.

2 The algorhitmic and parametric mechanisms are elaborated in the paper: Larsen, N. M., Egholm Pedersen, O., & Pigram, D. (2012). A method for the realization of complex concrete gridshell structures in pre-cast concrete. In Cabrinha, M., Johnson, J. K., & Steinfeld, K. (Eds.), Synthetic Digital Ecologies. (pp. 209-216). United States of America: The Printing House Inc, WI.

FOCUS: TECTONICS

The case utilised the theoretical assessment of the term 'tectonics', as presented in chapter two. The consequences for form, when material or technique is changed, were primary drivers for the design of both the overall form and the individual concrete elements. Hence, the purpose of the case was to illustrate relations between a concept (idea), the material (concrete) and the technique (a mould material subjected to a technology), as presented in the final construction.

As inspiration for the overall form, compression-only vaults are chosen. The concept of concrete vaults has been impressively exploited by Heinz Isler[3] and Felix Candela[4] (figures 2 and 3), who built numerous form-found compressive vaults throughout their careers. These projects were all cast in-situ, and required large amounts of timber falsework to be constructed (figure 4). The designs could be described in terms of basic geometry in order to ease production of this falsework. Such casting principles are rare today because in-situ casting is costly and it is easier to achieve high precision and high quality concrete when casting elements in a controlled environment. Also, despite their inherent complexity and fluidity, the need for a repetitive geometry limits the ability to adapt such construction principles to different situations.Recent work at the University of Manitoba by Mark West and others[5] has seen experimentation into the use of precast concrete elements within load bearing shell and vault structures, using flexible formwork and allowing gravity and hydrostatic pressure to generate form (figure 5). The method described in this case study differs from West et al.'s approach in that it uses more rigid, foldable moulds to cast smaller planar elements where the overall curvature of the system is a consequence of angled joints.

Figure 3: Compression-only shell for Deitlingen Service Station in Switzerland by Heinz Isler

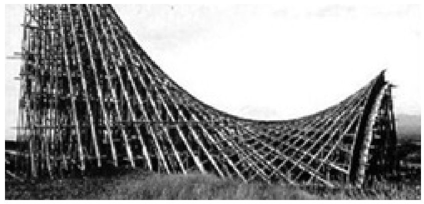

Figure 4: Falsework for the Xochimilco restautrant.

Figure 5: Fabric cast funicular concrete vault. By C.A.S.T at the University of Manitoba

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3 John C. Chilton, Heinz Isler: The Engineer's Contribution to Contemporary Architecture (Thomas Telford, 2000).

4 Billington Sr, D, and Moreyra Garlock, M, Felix Candela (Princeton University Art Museum, 2008)

5 West, M. 2009. Thin Shell Concrete from Fabric Molds. http://www.umanitoba.ca/cast_building/assets/downloads/PDFS/Fabric_Form work/Thin-Shell_Concrete_From_Fabric_Forms_SCREEN.pdf. Accessed 14 May 2012.

INITIAL CONSIDERATIONS ABOUT FORM

To enable the design of a compression only structure to be constructed from mass-customized concrete elements, funicular form-finding techniques based on dynamic relaxation previously developed by architects Dave Pigram and Iain Maxwell were chosen as a governor of the overall form of the structure.

This method digitally mimics Antoni Gaudi's hanging chain models made for the Sagrada Familia Cathedral in Barcelona. In the physical model, the chains take on forms or consists of that contain tensile forces only (catenaries) through physical self-organisation. When the hanging form is inverted, the forces are translated into pure compression, resulting in funicular forms optimized for construction in materials such as stone[6]. The self-organising process can be described by using Hooke's law, which states that for elastic deformations of an object, the magnitude of its deformation (extension or compression) is directly proportional to the deforming force or load. Algebraically, Hooke's law states that the applied force F equals a constant k multiplied by the displacement (change in length) x, thus: $F = kx$[7].

In order to be able to re-create the hanging chain model digitally, the formula is implemented in the computer application *ReVault*. This allows for real-time adjustments of factors such as spring length. In turn, this provides a massive increase in the number of possible solutions that can be explored within a limited time span, as compared to physical models.

METHOD DEVELOPMENT

It proved practical to divide the method into two parts. The first investigated form generation and the production of information for manufacture and assembly. The second was concerned with production and construction. Basically: a virtual and a physical part. In reality, the virtual and the physical parts are interlinked, which is a key property of the method (figure 6). Information

6 Bloch, M DeJong, and JA Ochsendorf, 'As Hangs the Flexible Line: The Mechanics of Masonry Arches', Nexus Network Journal on Architecture and Mathemathics Vol. 8, No. 2 (2006)

7 Kilian, A and JA Ochsendorf, Particle Spring Systems for Structural Form Finding. International Journal of Shell and Spatial Structures, Vol. 46, No. 2 (2005)

and material flows through the system in a cyclic design procedure, including all aspects of the realization process, through form-generation, production and construction. It breaks from a linear design process, where information concerning production and construction is confined to the later stages of the development. A digital form-finding process able to simulate the self-organisational behaviour of a network of springs was implemented in the programming language *Processing* by Iain Maxwell and David Pigram for this project based on earlier research. The benefit of this custom implementation comes from integration into the later workflows of creating 3-dimensional components around the force network, completing their unrolling for laser-cutting etc. Additional display modes have also been added to inform the real-time adjustment of factors such as spring length used to influence the vault's final form.

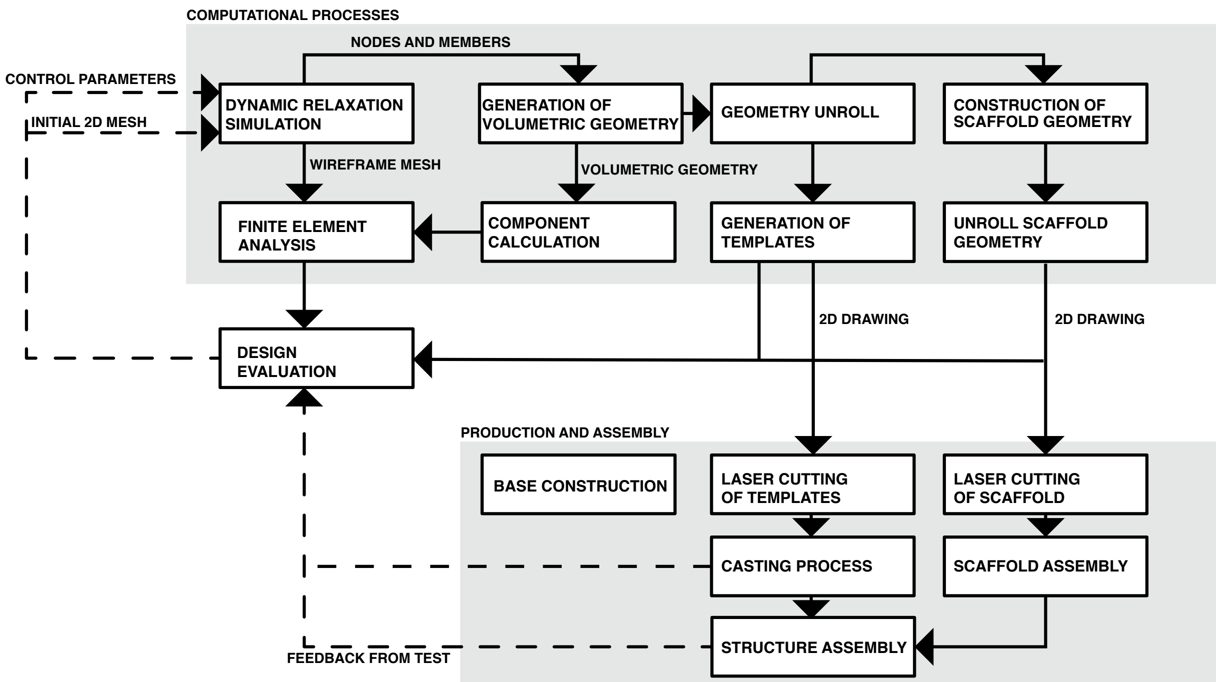


Figure 6: Process diagram

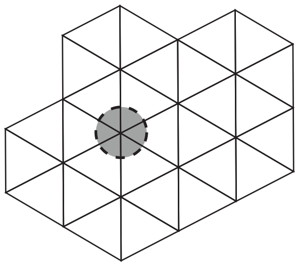


Figure 7: The definition of a mesh as triangles result in six-arm components.

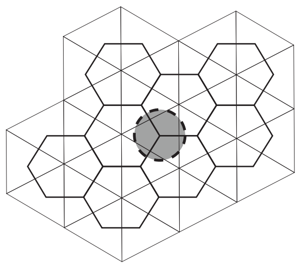


Figure 8: Re-meshing a triangular grid into hexagons reduces the number of lines meeting in a node.

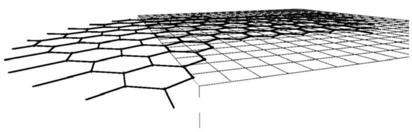


Figure 9: Input mesh imported as 2D drawing.

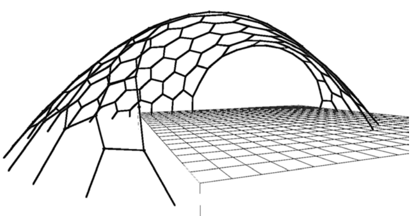


Figure 10: 3D mesh in equilibrium state after running the dynamic relaxation simulation.

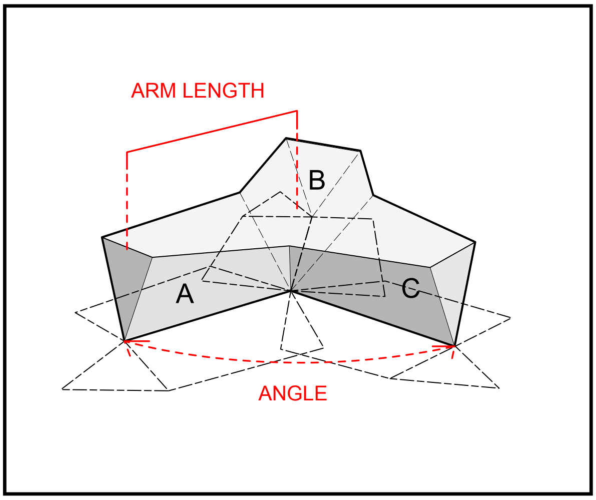
DEVELOPMENT OF GEOMETRY

The process of generating a compression vault from concrete elements was initiated by defining an overall geometry of the components. An open grid shell structure was favoured over a closed surface shell, in order to arrive at concrete components which are in essence a scaled down version of the beams produced in the 'Hello World' case study. When translated into a wireframe mesh, a double curved surface can be described as triangles (figure 7), or as hexagons (figure 8). A hexagonal mesh was chosen because a hexagonal mesh has fewer lines. Importantly, this means that the nodes represent a meeting of only three lines, whereas a node in a triangulated mesh represents the meeting of six lines. This allows for simpler component geometry, while the structure gets a lighter appearance and lower weight. A consequence of defining a hexagonal mesh is that the hexagons are not planar, but the 'Hello World' case study suggested that it would be possible to achieve sufficient precision in the castings to allow them to meet at an angle.

The digital form-finding process was established to accept an initial mesh or network of lines. While the modelling software accepted an arbitrary topology, a hexagonal mesh was drawn in order to achieve the benefits described above (figure 9). A series of fixed points were defined, which would remain fixed to the ground. When executed, the system runs the algorithm in a series of iterations until it arrives at an equilibrium state (Figure 10). Forms generated through the dynamic relaxation form-finding processes are optimised in terms of compression-only force distribution from the structure's own weight.

COMPONENT GENERATION

In order to translate the mesh into a series of concrete elements, a definition of the component geometry was needed. In order to utilise the circumstances in which the concrete can take up complex forms, it was



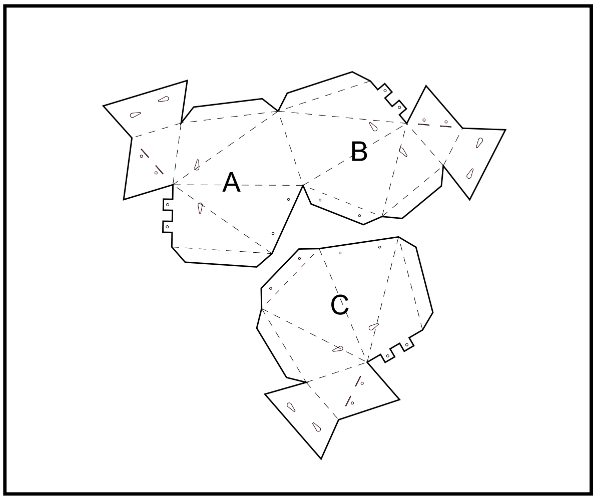


Figure 11: Variables in a component and the corresponding component template

practical to design the components around the nodes and let two components meet on the line between nodes. It follows that each component would be Y-shaped, with variable arm lengths and angles and meet the neighbouring element at an angle to deal with the non-planar nature of the hexagons (figure 11).

In order to generate the individual components, the wireframe geometry, generated through the ReVault simulation, was imported into 3D modelling software with a module for scripting[8]. The geometry was developed into unique volumetric components via custom written algorithms (Figure 12). In the same script, input for the manufacturing process was generated. This included scoring lines for folding, rivet holes, the engraving of a unique number (figure 13) and information which was used to generate cutting templates. Once cut, the templates were folded, joined and concrete poured (figure 14).

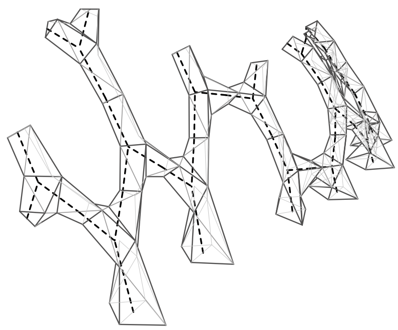


Figure 12: A three-dimensional line network (dashed line) forms the basis for parametrically generating the component geometry.

8 In this case McNeel's 3D modelling software Rhinoceros and its implementation of IronPython were used.

‘WORST-CASE’ PROTOTYPE TEST

Before the production of the final construction was initiated, it was decided to make a ‘worst-case’ test construction in order to discover in practice many of the constraints that would guide the final method. The hexagons in the prototype were constructed on the basis of a triangular mesh, which was transformed with the dynamic relaxation procedure (figure

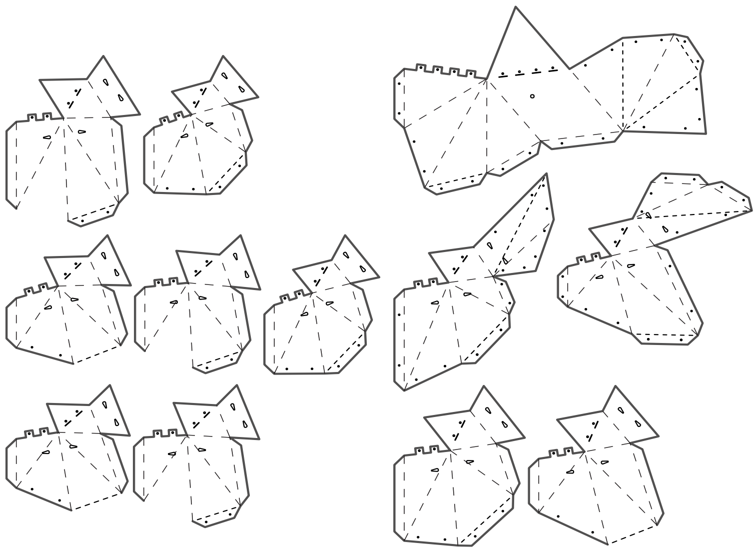


Figure 13: unrolled mould templates.

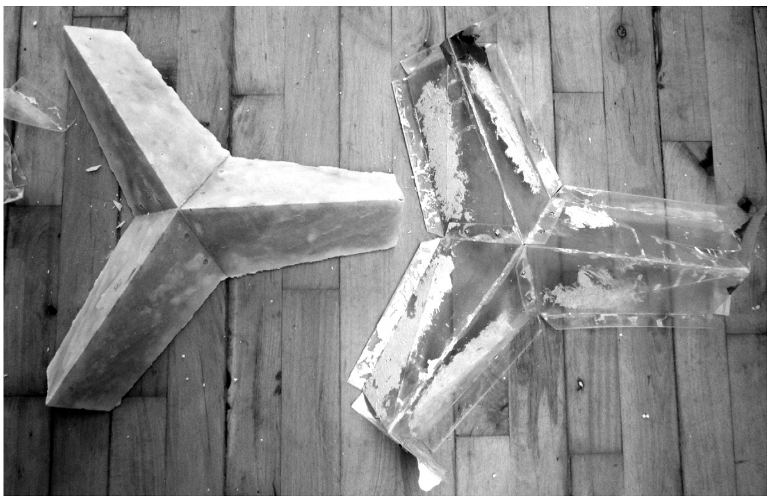


Figure 14: Prototype of Y-shaped concrete component and template of PETG plastic.

15). The structure was completely symmetrical, unlike the final construction. Through generation of the geometry, the mesh was translated into the hexagonal pattern, from which concrete elements were generated.

Finite Element Analysis showed that the use of a triangular mesh resulted in deviations from the optimised shape which were bigger than the component joints would be able to handle. Therefore, the principle was changed so the base geometry was defined as hexagons, and represented the final geometry more directly (Figure 16).

The prototype test illustrated the importance of connections. Correct positioning of each element was next to impossible without dealing with shear forces between the elements. This meant that the assembled form would not match the computed load paths, the construction would not be compression-only (even only under self-weight) and would collapse due to the lack of tensile resistance at the joints (Figure 17).

This translation resulted in a noticeable deviation from the catenary grid shell. Coupled with the fact that the joints in the prototype could not absorb any kind of shear or tension forces, this meant that it was impossible to assemble the prototype. Another finding was the importance of correspondence between initial and final mesh geometry. The test also showed that the use of tension cables to counteract the horizontal forces

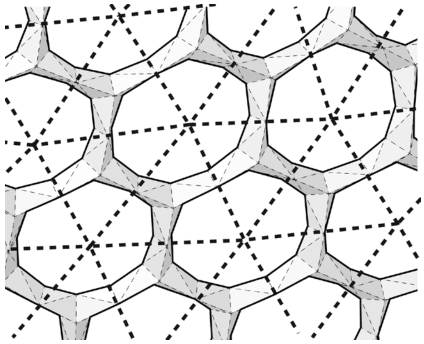


Figure 15: Initially, a triangular mesh was translated into a hexagonal mesh.

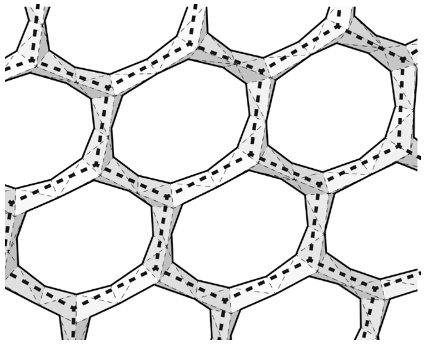


Figure 16: Hexagonal mesh, corresponding directly with the final structure.

Figure 17: The ‘worst-case’ prototype after structural failure.

proved difficult to control. In the final structure, the components were connected with structurally rated cable ties. Each cable tie can withstand approximately 0.9kN, providing a safeguard against unexpected forces, e.g. from human intervention.

THE REVAULT PAVILION

The case study was carried out at Aarhus School of Architecture in the autumn of 2011. Over the course of three weeks the authors with the aid of civil engineers Jacob Christensen and Ronni Madsen and twelve Master of Architecture students, designed and built a 16 square metre by 2 meter tall pavilion consisting of 110 discrete concrete elements, cast in PETG.

The case study was to be exhibited at 'Aarhus Festuge' - the 2011 Aarhus Cultural Festival. Given the experimental nature of the construction, it was necessary to perform an initial test assembly to verify its structural integrity. Hence the structure was assembled and disassembled twice: once at Aarhus School of Architecture and once opposite the Museum of Art in Aarhus. Anticipating this, the structure was designed with the capability of being disassembled. This made the use of mechanical (as opposed to cast) joints between the components practical. The ultimate component design resulted from the negotiated input of a large number of constraints such as structural strength, reduction of weight, sufficient volume for reinforcement, fabrication tolerances and assembly time. Of similar significance and intimately related to the compo-

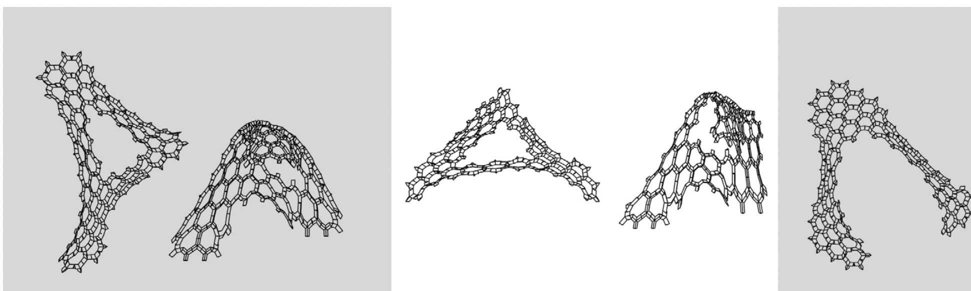


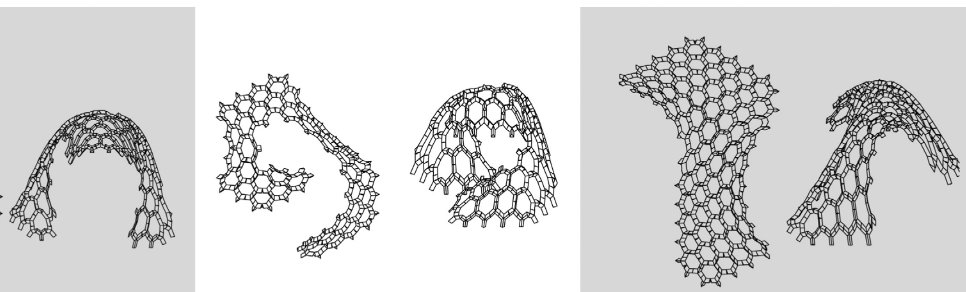
Figure 18: Investigation of different possibilities. The structure at the far right was chosen.

nent design, was the challenge to find a suitable joint solution manageable in terms of both production and economy. A production workflow, where the geometry was transformed between two and three dimensions according to the different parts of the process, was based on digital form generation and digital production logics. Algorithmic workflows allowed for the components to obtain their necessarily unique form and dimensions without major increase of the production time. This process was exemplified the in cyclic design and fabrication feedback loop.

The established design method allowed for a massive increase in the number of possible solutions which could be explored within a limited time span, as compared to physical models. For the case-study pavilion, the time for establishing the geometry of the structural mesh represented a total of three working days for one person. In this time hundreds of simulations were completed, allowing the designer to develop a sophisticated understanding of the behaviour of the digital system (Figure 18).

Once the overall design was decided, the script was run and output for the laser cutter generated. The pavilion structure design was comprised of 110 components, which was nested onto 900 x 1600 millimeter sheets of PETG and laser cut.

Fabricating the components essentially meant setting up a production line with stations for folding the PETG, riveting parts together and adding features, such as reinforcement (Figure 19), then filling them with concrete (fig-



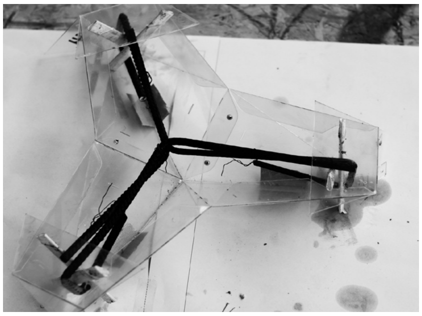


Figure 19: Template assembled from PETG with rebar installed

ure 20). Deformations of the PETG plastic did occur despite the elements being significantly smaller than in the 'Hello World' case study. This was solved by reinforcing edges with folds, triangulating large areas and by limiting the area of planar surfaces. These measures contributed to the highly specific set of aesthetic characteristics that accompanied this method (Figure 21).

FORCES IN THE STRUCTURE

When performing Finite Element Analysis the end nodes had to be fixed in order to resist lateral forces at the springing point of the grid shell (figure 22). In other shells, this is achieved through in-ground footings, but where such footings are impossible, such as in the shells of the Sydney Opera House, establishing connections across the structure at the ground level can also resist lateral forces. In the case-study pavilion, the forces were transferred through a plywood floor plate that engaged the

Figure 20: PETG Template filled with concrete.

Figure 21: The concrete components were triangulations in order to reduce deformations

bottom row of components, as each component rested in a shoe attached to the floor plate (figure 23).

In order to accommodate these improvements into the component generation script, distinctions between regular components, edge components and base components, were made, generating a flat base for base components (figure 24).

Furthermore, the analysis was used to calculate the shear forces in the joints, which again was used for making decisions regarding the joint design and materials. Theoretically there would be no shear forces in the joints, the structure supported by pure compression. In reality, shear forces did occur, due to the large openings in the mesh and due to lack of precision, both in the production of the components and in the process of assembling the structure.

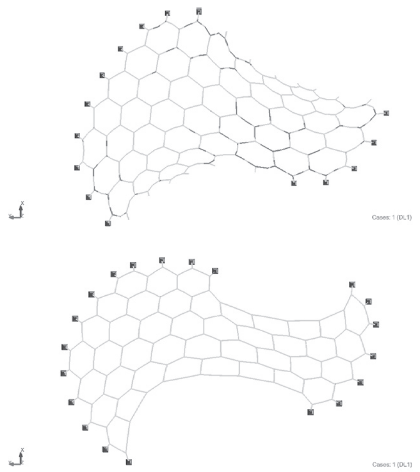


Figure 22: Plan diagram showing the bending forces in the structure.
Thick line: Significant bending forces. Thin line: No significant bending forces.
Top: Preliminary design. Bottom: Optimized final structure.

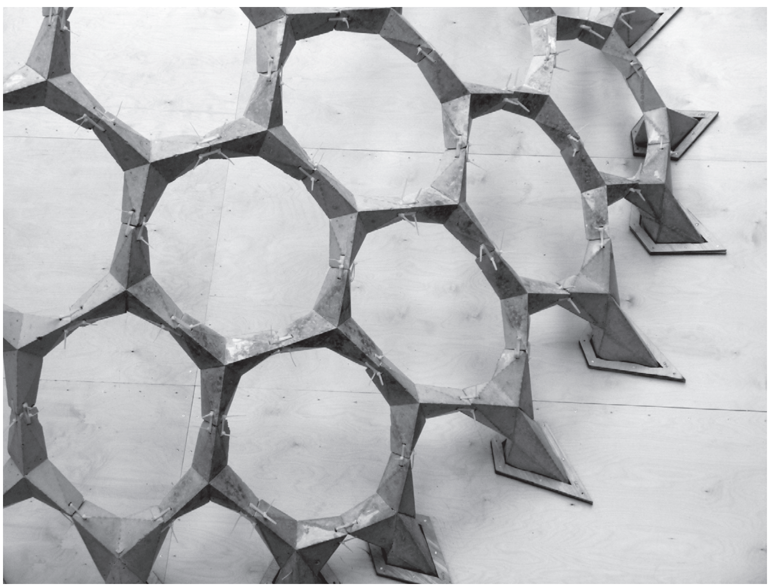


Figure 23: Regular and base components.

Figure 24: Base component

ASSEMBLY OF THE STRUCTURE

Given the relative thinness of the elements used in this method it is extremely important that the final construction matches the computationally found form so that all load paths remain within the sectional profile. Additionally, as is typical in non-Catalan vaults, the structure is not stable in an incomplete form.

As such it is necessary to use formwork to ensure the exact positioning of every component and to support them during assembly. Like the precast components, each scaffolding element is unique. The 3D component model was used for extracting the geometry of the falsework and for positioning the individual components during the assembly. The scaffolding was produced from cardboard, laser cut and assembled, first into triangular tubes, then into larger clusters forming hexagonal geometries, reflecting the plan of the concrete structure (Figures 25 and 26). The function of the scaffold is both to support the structure during construction and to ensure the exact positioning of the components, the latter aspect being most important, since very small deviations from the spatial geometry made assembly impossible. Component placement on the scaffolding was directed by unique identifiers, matching a component's arm to the corresponding arm on the neighbouring component.

The ReVault pavilion was erected and exhibited indoors (figure 27-29), then moved to an outside location where the pavilion served as landmark for a cultural event (figures 30-32).

Figure 25: The pavilion was assembled on top of a digitally generated, laser-cut cardboard falsework.

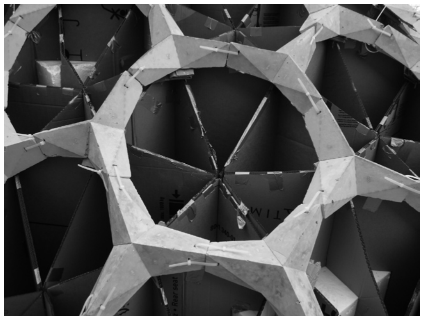


Figure 26: Falsework detail.

ANALYSIS

The technique proved capable of generating highly complex concrete elements, whilst maintaining a high level of precision. The use of scripting tools in the realisation process enabled the necessary generation of mass-customisation. Due to structural optimisation, material use in the construction is reduced and the material waste from the production of moulds is minimised. This is achieved through digital production tech-

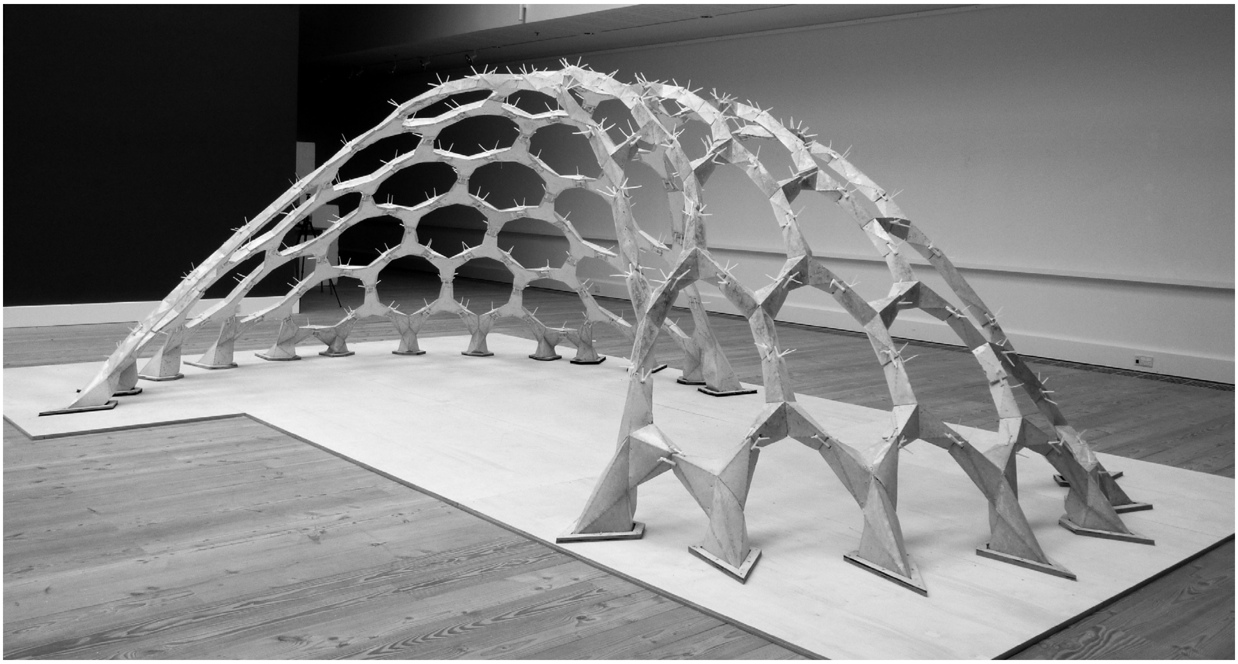


Figure 27: Concrete grid shell pavilion, first installation, Aarhus School of Architecture. October 2011.

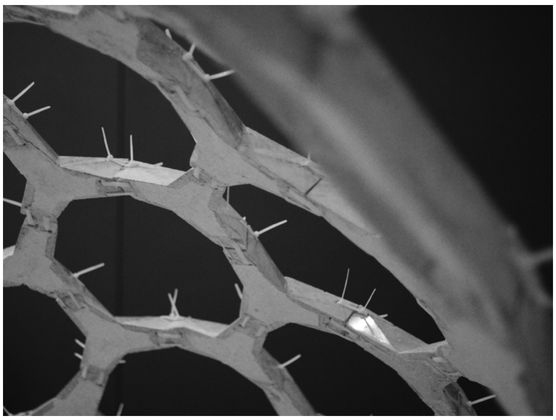


Figure 28: Inside the ReVault pavilion

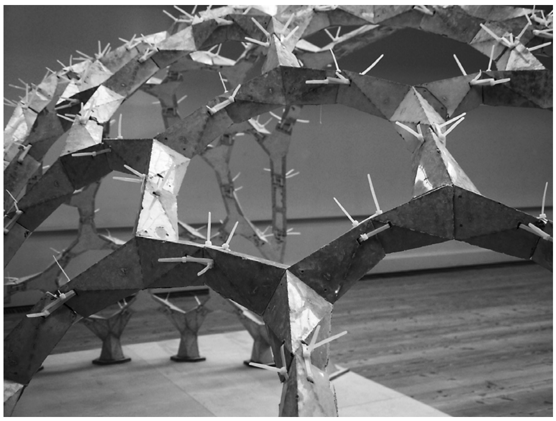


Figure 29: Dynamic shine transferred to the concrete from the PETG moulds.

Figure 30: Concrete grid shell pavilion, second installation, Ridehuset, Aarhus. October 2011.

Figure 31: The second assembly was carried out in three hours.

Figure 32: The ReVault pavilion was part of an exhibition at the AArhus Cultural Nighe 2011.

niques and the possibility of recycling the PETG moulds. As such, the method suggests a more sustainable approach to complex concrete structures. The case study addresses the methodology and the system of form-generation and production, and records a description of the experiments carried out, including findings that were observed during experimentation.

With the continuous development of new production technologies, the question arises, whether it is possible to suggest a design strategy that will allow for the design of fully mass-customised concrete elements. Computational design techniques and Numerically Controlled (NC) fabrication equipment enable production that breaks away from the industrial paradigm of standardization yet these possibilities have not had a significant influence on the production of concrete building components. There are several reasons for developing new methods of concrete casting as an alternative to the traditional mass-produced steel or plywood forms. Digital design-to-production processes enable variability and increased complexity in mould form, whilst maintaining very high precision levels. The use of simulation software allows for the integration of structural analysis and optimization in the design process.

CONCLUSION

Custom-made scripts embedded in 3D-modeling tools were used for producing the information necessary for realising the construction comprised of discrete concrete elements.

In the case study pavilion, later described in detail, Y-shaped components (Figure 4) were practical, but the overall method in general and the casting method in particular can accommodate other component geometries and structural forms. An important conclusion is that not every component geometry or overall form of is possible: certain tectonic rules need to be obeyed. Restrictions include the size of moulds and the fact that a flat-bottom component is necessary in order to be able to stabilise the mould during casting. Also, the meeting between components has to be simple. As such the system may be said to allow for a ruled formal freedom.

As long as these rules are taken into consideration, one can conclude that the proposed method allows for the design and fabrication of complex funicular structures from discrete precast concrete elements. The research proposes that through the integration of digital form finding techniques, computational file-to-fabrication work flows and innovative sustainable concrete casting techniques, complex funicular structures can be constructed using prefabricated elements in a practical, affordable and materially efficient manner.

The case study's goal was to investigate how computation, material innovation and digital production technology enable feedback loops in the design process, to establish stronger connections between design and production and to develop new sustainable production methods.

The case study pavilion, constructed in a very short time, at low cost and with relatively unskilled labour, demonstrates that the integration of algorithmic form-finding techniques, CNC fabrication workflows and the use of innovative PETG folded mould techniques enables the practical realisation of freeform funicular structures in pre-cast concrete.

CHAPTER 12: PLAYVAULT

Figure 1: The PlayVault Pavilion

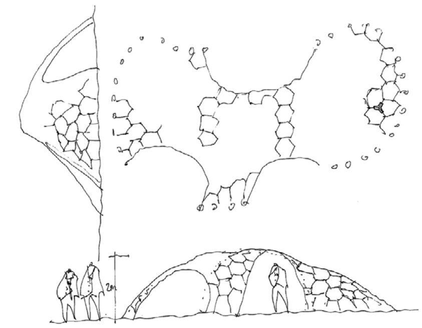


Figure 2: Initial conceptual sketch

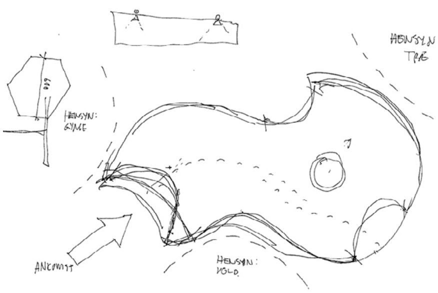


Figure 3: The conceptual scheme which was realized

INTRODUCTION

PlayVault was carried out as a workshop with forty students over a period of two weeks at the Royal Academy of Fine Arts in Copenhagen, Denmark. The case study served two purposes: to test the method in an industrial production outside the laboratory and to explore the potentials of the method to deal with a more complex overall form.

PROCESS

The overall concept was established on a basis of the design brief and an assessment of what could be achieved within the workshop budget (figures 2 and 3).

A revised version of the dynamic relaxation algorithm was developed and implemented as a Grasshopper component in order to keep the digital development of geometry within a single piece of software, namely Rhinoceros 5.0. This allowed students to quickly learn the workflow of drawing a flat mesh in Rhino, performing dynamic relaxations and refinements (Figure 4). This enabled many designs to be proposed and evaluated in terms of ability to meet the design brief and structural performance[1]. The chosen design was a concept of a structure which had a tall end with a height of two meters, presenting itself as a structure to climb and a low end nicknamed *the doughnut*. In the low end, the mesh has a hole in the middle with the component arm ends defined as base components; upon dynamic relaxation, this generated a circular tunnel with a height of just one meter. The result was a structure with a greater geometrical complexity than the ReVault pavilion, consisting of 190 discrete components (figure 5). The components were designed slightly larger (about 15%) than the ones used in the ReVault case study, which would allow for the application of greater loads to the structure.

1 As in the ReVault case study, structural performance evaluation included assessment of tensile and shear forces using Autodesk Robot ®

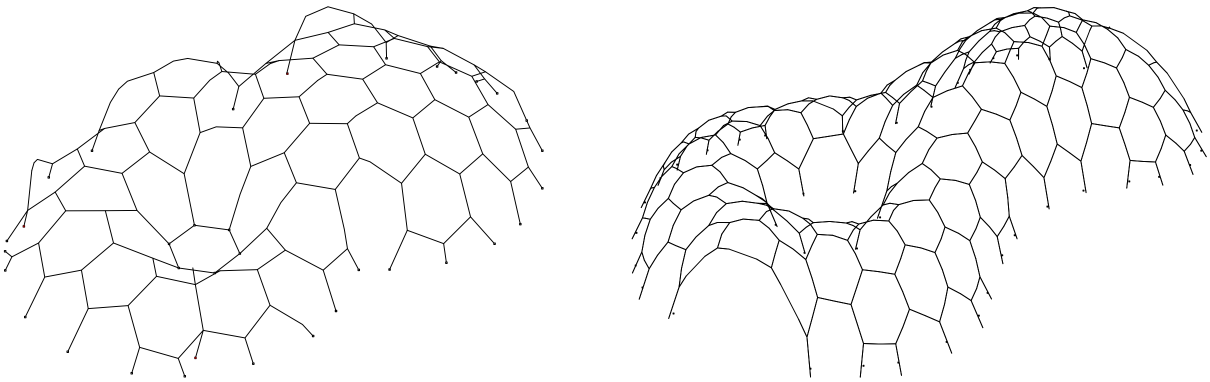


Figure 4: Development and refinement of the geometry using Rhino and a dynamic relaxation component in Grasshopper.

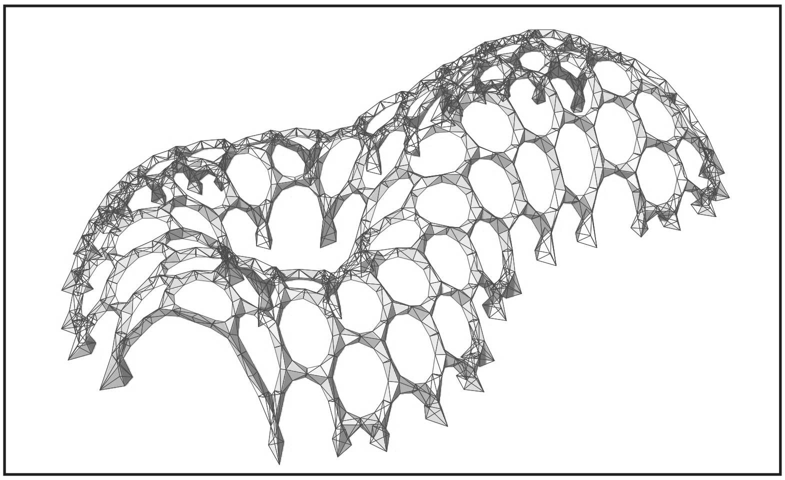


Figure 5: The final design for the PlayVault pavilion, consisting of 190 discreet components.

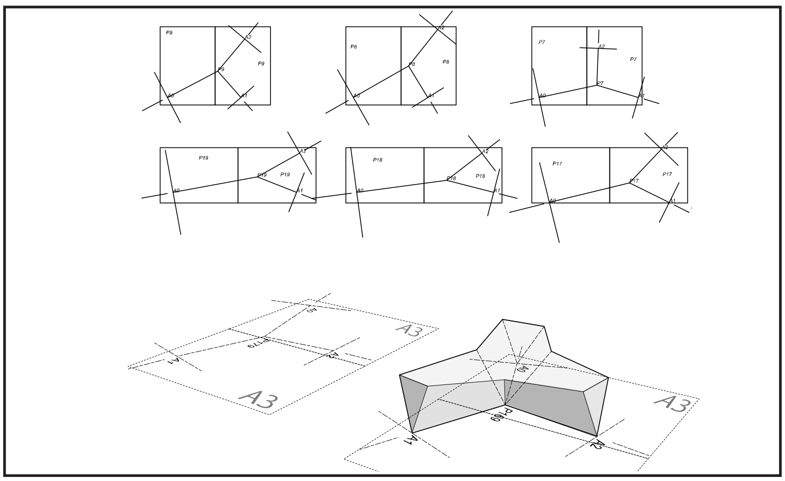


Figure 6: Blueprints generated from the digital model allowed the precise positioning of components.

Figure 7: production of 190 discrete concrete component

Figure 8: Without the ability to digitally manufacture the supporting falsework, its assembly presented the biggest challenge during construction.

The method of printing blueprint templates for the components developed in the ReVault case study was applied to ensure the precise positioning and angles of component arms (figure 6). In order to avoid reinforcement, plastic fibres were used in the concrete mix to resist smaller tensile forces in the structure. This reduced the complexity of the moulds and shortened the time needed for assembly, which was completed in less than two days (figure 7).

As construction was about to commence, the fabrication equipment which was to be used for cutting the cardboard templates went out of service. This meant that the falsework had to be drawn up and cut manually. As a result construction of the falsework becamean immensely complicated undertaking (Figures 8 and 9). Firstly, it led to a loss in precision, as well as to folding and mirroring errors that digitally controlled cutting and marking could have avoided. Secondly, it prolonged the manufacturing of the falsework to a point where it was impossible to produce all of the supporting cardboard hexagons needed. The missing hexagons proved disastrous for the erection of the structure, as it turned out to be impossible to position all of the components precisely within the limits of the ideal compression-only arc. Hence, the structure became unstable and

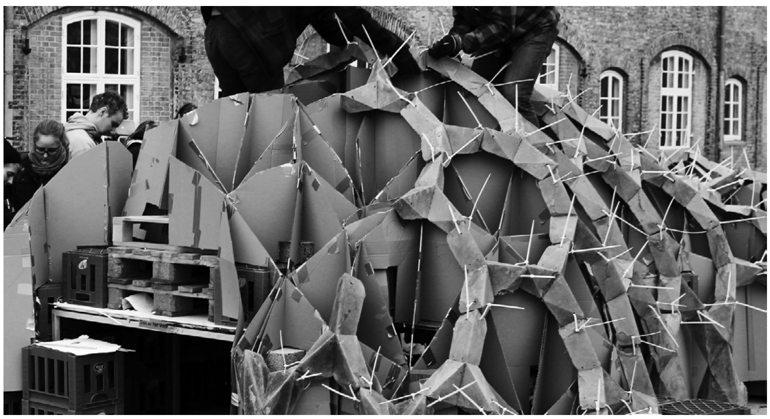


Figure 9: An imprecise falsework hindered the correct positioning of components.

Figure 10: The structure needed supports in order not to collapse

Figure 11: Inside the PlayVault structure.

Figure 12: The PlayVault pavilion


Restaurant & café

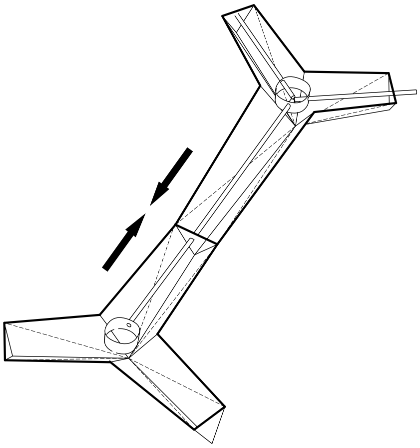


Figure 13: The development of a joint in the centre of the mould.

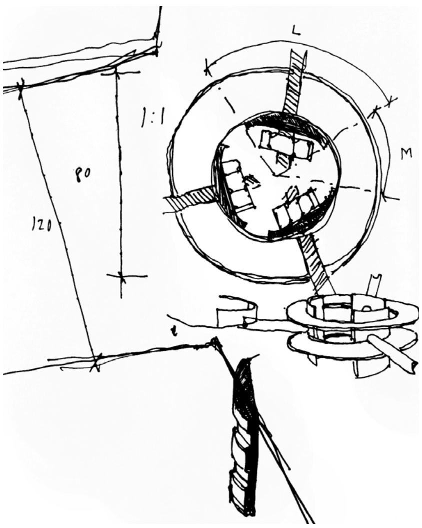


Figure 14: Sketch for a detail allowing for post-tensioning of steel rods in the center of each component.

needed supports in order not to collapse (figure 10).

CONCLUSION

The case study gives rise to conclusions regarding the design and the manufacture.

Small design changes had a great impact on the performance of the pavilion. The decision to upscale the components resulted in greater deflection of the PETG mould which in turn decreased the precision of the elements. The structure's base components were attached to an existing concrete surface with a steel pin. This turned out to cause the components to rotate away from the ideal position, which had consequences throughout the structure and reduced its stability. In conclusion, the PlayVault pavilion can be said to illustrate the limits of what the building principle can accommodate: small design changes and flaws have great consequences and resulted in a less convincing result than the ReVault pavilion.

The case study did, however, prove that it is possible to create complex overall geometries, which respond to a specific brief (figures 11 and 12). Furthermore it illustrated that the manufacturing is sufficiently simple to take outside the laboratory and into a commercial production line. The case study also showed that the use of fibre reinforcement is advantageous when the mould geometry is complex.

It was impossible to position all of the components within the compressive arc because of the difficulties in manufacturing the cardboard falsework. This would have been easier, if the components were pulled together tighter than the zip ties allowed. This gave rise to a proposal for a design change, which could be developed further; namely a duct running laterally through the component arms, inside which a steel rod or wire runs from the centre of one component to the centre of the neighbouring component (figure 12). By adding a cylindrical insert which houses a relatively simple steel detail in the centre of the component, the steel wires are connected and tensioned (figure 13). This enables the transformation of tensile forces from component to component, thus activating the ring-forces in the entire structure. This in theory would allow for construction without a scaffold and greatly enhances the construction´s ability to carry the loads that are applied to the compressive arch.

PART VI
ANALYSIS AND DISCUSSION

CHAPTER 13: CONCRETE TECTONICS

INTRODUCTION

The case studies are analysed across three levels. Firstly they are categorized into two themes: Potential in existing techniques, and novel techniques, followed by a summary of the qualities and weaknesses of the examined casting methods.

Secondly, a more general analysis regarding tectonic relations in mould making is offered, relating to the account of tectonics presented in chapter two.

Thirdly, a similar analysis is offered with a focus on concrete tectonics.

The concept of mould tectonics and concrete tectonics is then exemplified with the folded PETG technique.

CASE STUDIES ANALYSIS

Conclusions found in chapters two to six gave rise to the case studies. which approach the research question from different angles and at different levels. A structuring of the case studies into four categories is proposed in order to represent the different angles: *Potential in existing techniques*, *elaborated design proposals*, *novel techniques* and *digital tectonics* (figure 1). There is a progression throughout the case studies: ‘under Pressure’ has the lowest level of complexity, as it is an isolated investigation of a novel technique. ReVault, on the other hand, draws on conclusions made in previous cases, while dealing with several different angles: Digital tectonics, the creation of a design proposal, and the development of a novel technique. As such the ReVault case study represents the highest level of complexity.

POTENTIAL IN EXISTING TECHNIQUES

A precondition for all case studies was that current developments in technology and production philosophies should be taken into consideration. These developments included *minimising waste*, *speed*, *digital design to production* and *mass-customization*. In the state of the art analysis, it was established that suspended textiles, hot-wire-cutting and CNC milling are technologies which have potential for individualised concrete casting. As described above, casting in suspended textile is hard to control and hot-wire or CNC milling technology is used with EPS, which gives rise to a problematic surface in the

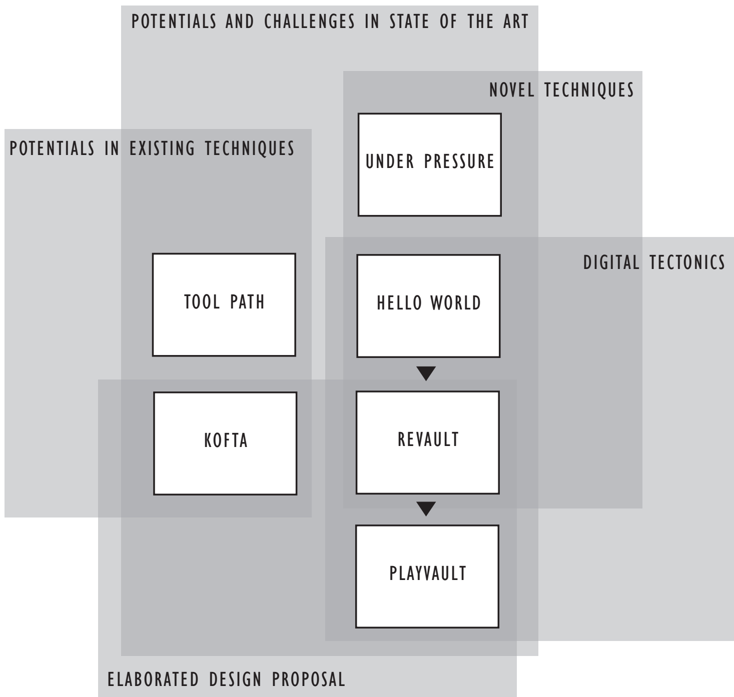


Figure 1: organization of the case studies

casting mould. The case studies ‘Kofta’ and ‘Tool path’ took precedent in an existing technique, and explored the uses of this technique architecturally. As such the cases illustrate a method – a way of introducing the possibility for an aesthetic evaluation of subsequent casting principles.

These techniques gives cause to work with two aspects of the design: firstly, linearity in one direction, curvature in the other. This should be a fundamental part of the formal logic, as examined in the *Kofta* case study. Secondly, concrete should be cast as elements, allowing the EPS to rest against an outer, standardized mould when the concrete elements are cast.

CNC milling as a mould technique shares many similarities with hotwire cutting, including the dependence on EPS as a mould material. The main difference is that CNC milling is slower, depending on the nature of the tool path. The case study ‘Tool Path’ established that an up-scaling of the drill bit and the introduction of rules about how the tool path is governed, may reduce the milling time while providing a hint of the geometry of the casting mould and hence the concrete castings. The surface, however, was found to be even more problematic with CNC milling, as the drill bit rips rather than cuts the EPS beads. The ‘Tool Path’ case study did not present an elaborated design proposal, but did suggest that individualized roof elements could be made. The sketchy and somewhat postulated nature of this suggestion reduces its validity, but with reference to the four challenges presented in chapter two, one could argue that the case study does have some justification insofar that it presents a new view on both the use of CNC milling equipment, and potentially the concept for novel roof designs. The main contribution of the ‘Kofta’ case study, on the other hand, is that it represented an elaborated design proposal. The proposal may be subject to critical revision, creating a space for contemplating whether its performance as architecture. The case study is arguably tectonic, but its value as a design proposal is questionable. Does it succeed in being both conspicuous and in agreement with the landscape? Or is it obtrusive and alien? Regardless of one’s stance, the case invokes a *phenomenologi-*

cal awareness of the implications of individualized concrete in the Norwegian landscape, which potentially enables new realizations.

In general, EPS is found to be the material of choice in the development of new industrialized and individualised concrete casting techniques. The primary reason is the material's low density, which makes it easy to cut or mill into amorphous shapes. Furthermore, EPS is inexpensive and allows for one-off moulds to be made with little or no waste generation, as the material can be recycled.

EPS was also found to have great potential for being manipulated into precisely defined, complex geometry and thus a high degree of *precision*. The nature of the material was found to be similar to concrete, in that EPS is made up of innumerable small beads, and thus does not have an inner structure which influences the overall form of the material, in contrast to wood which is fibrous and thus linear. The result is that the material may be said to possess a *formational flexibility*, allowing the technique to dictate how the EPS is formed. It was found, however, that the application of subtractive techniques such as CNC milling or hot-wire-cutting destroys the surface, resulting in a poor *surface quality*.

NOVEL TECHNIQUES

The development of a novel technique was commenced in the case study 'Under Pressure', set forth by a wish to deal with the surface problem. The case study builds on conclusions regarding the *New Production Philosophy*, dealing with problematic flows in two existing techniques: CNC milling and the ADAPA adjustable casting table. That is: a re-thinking of the time consuming nature of the two processes. Furthermore, the case study proposes a technique which inherently points towards *mass-customization*.

The aspects of *resource-minimization* led to the proposition of a novel technique involving laser cutting combined with folding of thin PETG plastic sheets as a means to achieve a lot of form with little effort, and little waste. In the case study 'Hello World' the mould making technique was developed using a laser cutter is done by cutting and bending, allowing for both a high speed production, digital design to production and mass-customization. Digital design to production, however, was only truly elaborated in the 'Hello World', 'ReVault', and 'PlayVault' case studies, in which a logical way to generate three-dimensional form from a flat sheet in ways that can be controlled parametrically, was developed. As such the case studies respond to the concept of *digital tectonics*, and the representational notion of *simulation*.

A high surface quality is achieved and the record of fabrication remains intact when casting against textile or rubber, materials which also allow for a high degree of formal flexibility. When fabric is used as a mould material, form is dictated by the weight of the concrete when it is poured and this makes is hard to control the geometry of the concrete. In other words, *precision* is a challenge. Rubber is used as a membrane which may be regulated with pistons, in which case the precision is high, but the formal flexibility is low, because castings need to be done horizontally. PETG was identified as a material with both a high quality surface and material properties which allow for folding. These folds were found to result in a high degree of precision as well as a ruled formal flexibility.

QUALITIES AND WEAKNESSES OF CASTING TECHNIQUES

Overall we can conclude that the task of making unique, one-off casting moulds is complex, both in terms of governing the mould design and in the actual making of the mould. Therefore, the mould itself – and in particular the material used should be as simple and easy to shape as possible. This simplicity of the mould involves eliminating or reducing post-processing of the mould material to produce the shape of the desired mould geometry. Post-processing also potentially obscures the visibility of the fabrication in the concrete imprint, weakening the relation between the form and its origin.

Based on the empirical and case study conclusions, five properties essential to the mould material are defined: a *simple process*, *amorphous form*, *complex form*, *surface quality* and *precision*. It can be concluded that a given mould material often excels in one property at the expense of others (figure 2). One can claim that subjecting the mould material to an assessment of the *tectonic logics* of the material is needed to deal with the possible opposing restraints. However, a single concrete casting technique that is able to address all these problems, does not exist. It follows that none of the case studies present themselves as 'the one casting technique to end them all'. It should be noted that these properties only deal with relationships within the making of the mould, not other aspects of casting techniques, such as their ability to be part of current concrete manufacturing processes, or strategies for assembly.

TECTONIC RELATIONS

The six case studies described in part III investigated how attention to the foundation of concrete tectonics and 21st century fabrication could affect the creation of casting moulds. The findings relating to *mould material* and *mould technique* are presented in order to propose generalised conclusions concerning the assessment of *mould tectonics*. The mould tectonics diagram was defined in chapter two as a way of positioning the mould material and technique into the process of concrete casting. This diagram was derived from the material-technique-form triangle, but it lacked the emphasis on *relationships* which is found in the triangle. Hence the proposal of a strategy for assessing mould tectonics will involve a further step: the definition and illustration of *relations* between the mould material, technique and form of the mould, indicative of the *concrete tectonic relations*, where concrete tectonic relations includes not only the mould, but also refers to the process of building with concrete. This leads up to a concluding discussion of concrete tectonics in the current building practice in chapter 14.

	HOTWIRE CUT EPS	CNC MILLED EPS	CAST EPS	FOLDED PETG LARGE SCALE	FOLDED PETG SMALL SCALE
FAST, SIMPLE PROCESS	YES	YES	NO	YES	YES
ALLOWS FOR AMORPHOUS FORM	YES	YES	YES	NO	NO
ALLOWS FOR COMPLEX (3D) FORM	NO	NO	NO	YES	YES
QUALITY SURFACE W/O TREATMENT	NO	NO	YES	YES	YES
HIGH DEGREE OF PRECISION	YES	YES	YES	NO	YES

Figure 2: qualities and restrictions in the examined casting methods

MOULD MATERIAL, TECHNIQUE AND FORM

With a tectonic approach to mould making, properties, characteristics, or performance of material and technique influence one another and give rise to the form of the mould. This attention to the *relationship* between *material*, *technique* and resultant *form* of the mould is pivotal in order to achieve moulds which are tectonic. Based on the findings in the case studies and the above conclusions regarding material and technique, a generalised description of these relations is proposed (figure 3). Based on the findings in the case studies, the following relations between mould material, technique and form are identified:

MOULD RELATIONSHIPS: MATERIAL – TECHNIQUE (A)

Considerations between *material* and *technique* concern how well the mould material is suited for use with a given technique. And the other way around , how well the technique performs in shaping the mould material:

-Is the process of shaping the material a quick one?
-Is the material and technique suited for mass-customization?
-Is it possible to use the technique 'as is' without any major modifications to it?

MOULD RELATIONSHIPS: MATERIAL – FORM (B)

Considerations between the mould material and the actual form of the mould revolve around material properties and the material's ability to take on complex shapes. This is primarily because the concrete with which the mould will be filled, is amorphous and allows for complex geometry:

-Is it possible to manipulate the material into complex geometry?
-Is it possible to achieve a high precision of the mould with the given material?
-Is it possible to achieve a high quality and closed surface?
-Do the material surface properties transfer to the concrete, once it is cast?

Mould relationships: technique – form (C)

Considerations of the relations between the mould making technique and the resulting form are related to the process of making. That is: how the technique performs and how it is governed:

-It a lot of form achieved using little effort?
-Is it possible to govern the process using computation?
-Is it possible to 'read' the technique in the mould which it creates?

Conclusion: Mould relationships: material – technique – form (D)

It can be concluded that the understanding of the possible tectonic relations in the casting mould
requires both a thorough knowledge of the material and technique and a critical approach as to how both perform, including what their weaknesses and strengths are. The questions listed above may serve as a guide in this assessment.

The relationships involving the technology used and the mould are of a technical character and may seem trivial, but these relationships are of great importance if mould tectonics is to be viewed as a means with which to achieve poetic constructions, as set forth in chapter two. The case studies ‘Kofta’, ‘ReVault’, (and to a lesser degree ‘Hello World’) all result in actual proposals, and may be seen as attempts to generate ‘poetic form’ using knowledge of both material and technology. In both case studies mould tectonics is developed as part of an actual building process, or put differently, as a *concrete tectonic relation*, which will be the topic of the next chapter. As the ‘Kofta’ mast remains a hypothetical example , and its appearance may well be less intriguing than expected if experienced as a build work, ‘ReVault’ perhaps is the best example of poetic form being the direct result of tectonic mould relations, because it was built, it *exists,* displaying the relations as a physical manifestation.

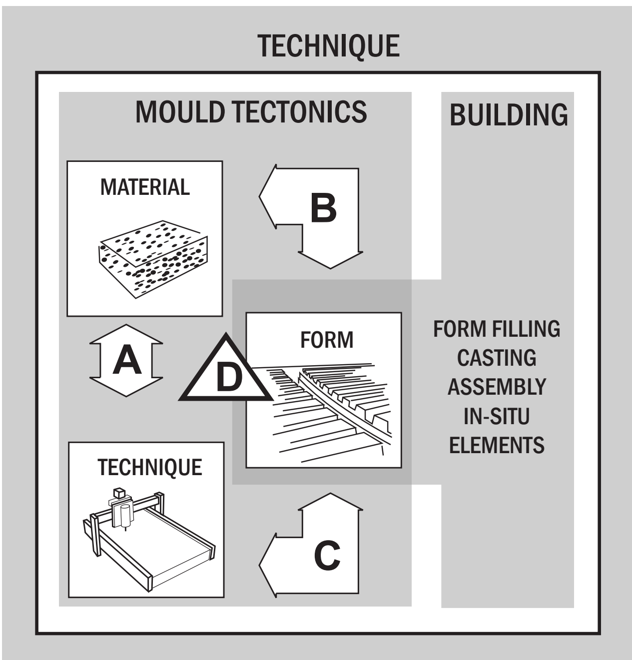


Figure 3: Mould tectonics diagram

CONCRETE TECTONIC RELATIONSHIPS

The analysis regarding *mould tectonics* can be assessed in a larger context of *concrete tectonics*, leading to a series of statements proposing an attitude towards act of making of forms in concrete.

Mould tectonics constitutes a part of the technique in the larger context of *concrete tectonics,* as stated in chapter two. As with the mould tectonics, each category (material, technique and form) may be assessed individually, in order to clarify their respective properties. With regard to the technique, the analysis of mould tectonics in chapter 13 serves as such an assessment. Regarding the *material* concrete, an account of all negotiable properties is outside the scope of this thesis, but two properties are emphasized: the material's inherent amorphous qualities and its ability to cope with pressure. As the form is a result of the material and technique, it is not assessed separately. Instead, attention is once again turned towards the *relationships* between material, technique and form (figure 4). These relationships stem from the tectonic triangle presented in chapter two and includes the mould tectonics which is now part of the technique. As such, this new diagram represents a higher level of pertinence, as it introduces the geometric *form* of the concrete*,* understood as both the conceptual ideas about form and finished construction and the *materials* understood as the concrete material.

MATERIAL - TECHNIQUE(1)

It can be concluded that analysing a concrete casting technique (that is: the mould tectonics) can form a basis for creating concrete elements which utilize or even express the properties of concrete. Properties which may be utilized in the technique, and easily reveal themselves, are the *weight* and the *isotropy*. When these properties are used actively as part of the technique, amorphous geometry - shapes in concrete can be produced which are complex in geom-

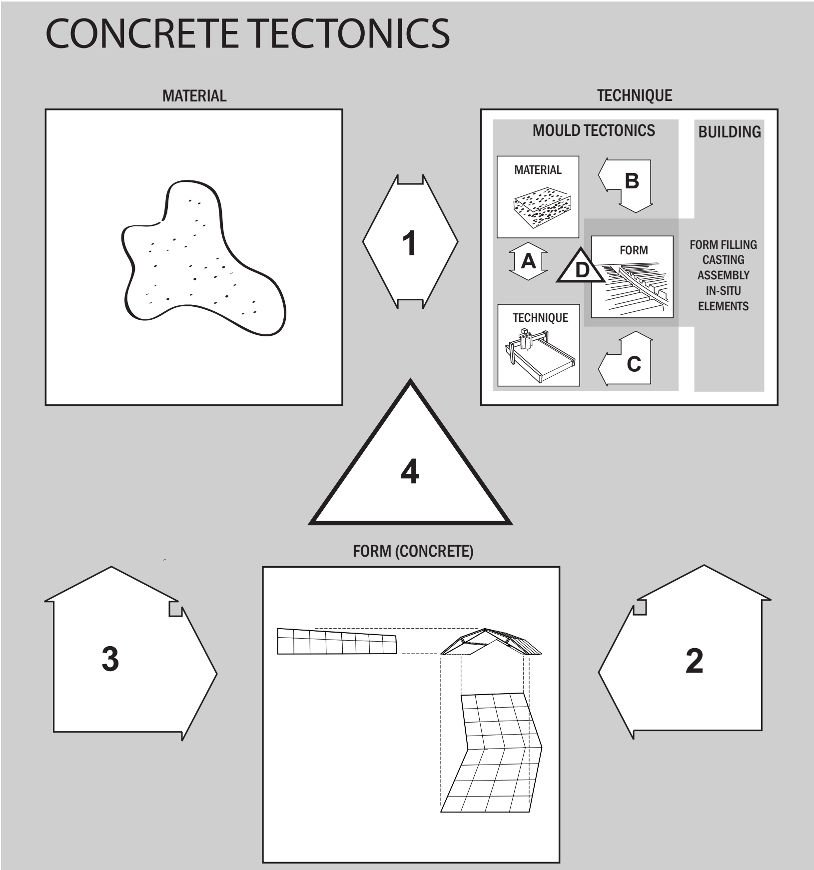


Figure 4: Concrete tectonics diagram.

etry, yet straightforward to produce. The following four questions address these possibilities:

- Is the concrete capable of adapting to the mould?
- Is the mould geometry capable of adapting the concrete?
- Can the mould material cope with - or even express- the hydrostatic pressure of concrete?
- Does the mould take into account - or even utilise - the amorphousness of concrete?

TECHNIQUE - FORM (2)

The primary focus of the relationships between technique and form lies in how tectonic forms in concrete may be conceived by means of addressing the potentials of the technique. This involves a cyclic design approach, in which the mould tectonics is developed alongside the overall formal concept, as illustrated by the development of the shells in the Sydney Opera House and tested in the case studies. We can conclude that a form is given tectonic qualities as considerations regarding *mould tectonics* necessitate an alteration and development of the initial idea about form, thus adding an extra layer of significance. We can also conclude that the development of complex forms in concrete and the use of complex techniques requires the establishment of a digitally based design loop, in which both form and manufacturing can be iteratively explored and developed.

As stated in chapter three, this use of digital tools used for creating form and for the realisation of these forms is the main difference between the industrialisation of modernism and the industrialisation of today. This requires a thorough understanding of digital design tools and their potential for complex, mass-customised concrete casting. It is crucial to understand the translation of a formal intention into something that can be yielded as physical form, because it is in this translation that a method for using the technique to generate tectonic form is hidden.

Put differently, the concept should be expressed as forms in concrete, fitting into the logic of the technique, while the technique should be able to sustain, or better, *enhance* the original architectural intention.

The relations are expressed in the following questions:

- How can the mould become a mediator between form and technique?

- How can the mould material and technique inform the overall idea about form?

- How may the technique sustain or even enhance the architectural intentions regarding form?
- How is the overall form broken down into parts fitting the technique – as elements or in-situ?
- How may the construction reveal the mould tectonics?

MATERIAL - FORM (3)

From the relationship between material and form, certain properties of the concrete material that are of relevance to the mould design can be suggested. The material property of concrete, for example its viscous nature – should be a determining factor of the mould design. This tectonic relationship between form and material is stated in the following:

- Are the proposed shapes realisable in concrete in such a way where the material and constructive properties are utilised and become part of the aesthetics - i.e. its shape ability and ability to cope with compressive forces?

- Is the concrete mixed in such a way that it is able to flow into the mould and are the properties or mix proportion of sand, cement and stones of importance to the characteristics of the cast concrete shapes?

MATERIAL – TECHNIQUE - FORM

The above relationship propose a design strategy in which the mould making technique is elevated to become a design parameter, rather than a means to achieve an already established formal intention. The empirical studies and the case studies approach an exemplification of such bespoke relations between form, technique and mould, or in some cases, lack of a relationship between the three. A common feature of the case studies was the central position of the mould as both a mediator of concept and an interface between form, material and technique.
This relationship may be summed up in the following statement:

A mould with tectonic qualities may be conceived by means of investigating the potentials of a specific technique. *This can be achieved by the technique necessitating restraints of alterations to the mould, or by adding an extra layer of meaning*.

AN EXAMPLE: FOLDED PETG CASTING PRINCIPLE

The concrete tectonics diagram is intended to be a help in navigating among the multitude of factors which influence tectonic concrete casting, which may be illustrated by an example: a synthesis of the relations considered in the folded PETG casting principle, by inserting the material, technique and form into the diagram:

The model, in this examples, is used to describe the complexity of dealing with the full set of relations and may be seen as a test of the model's viability as a guide in exploring the tectonic potentials of concrete. Of the three casting principles investigated (hotwire cutting, EPS casting, and PETG folding), PETG folding is considered the most advanced, in that it incorporates a digital approach to form generation as well as constructive considerations.

As such, the description of this casting principle by means of the concrete tectonic relations diagram helps illustrate the model's ability to serve as a tool that activates the sum of considerations from which a tectonic result originates.

The development was initiated by a hypothesis, which lies on the *concrete tectonics level (*Figure 5, [4]), namely the assumption that the use of computer controlled casting *techniques* (and) allow for the creation of complex *forms*, realising the potential of the concrete *material*, along with a more optimised process and use of the material.

An assessment of existing casting techniques then established that deformation represents an interesting approach, as it allows for the generation of a lot of form using little technology. Also, the relation between material and technique was found to be strong (figure 5 [1]), as the deformative materials typically leave a high quality surface in the concrete(,) and that the weight of the concrete creates the form. Current research, however, does not incorporate the precision and control found in digital fabrication. This led to a choice of method: deformation; and a technique: laser cutting and folding of PETG

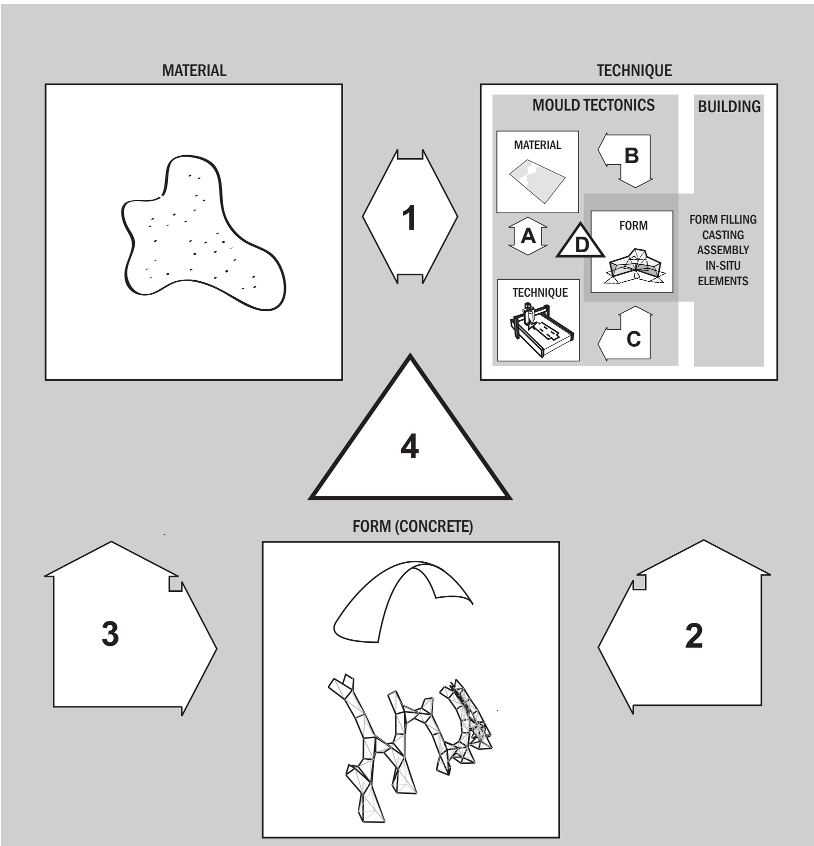


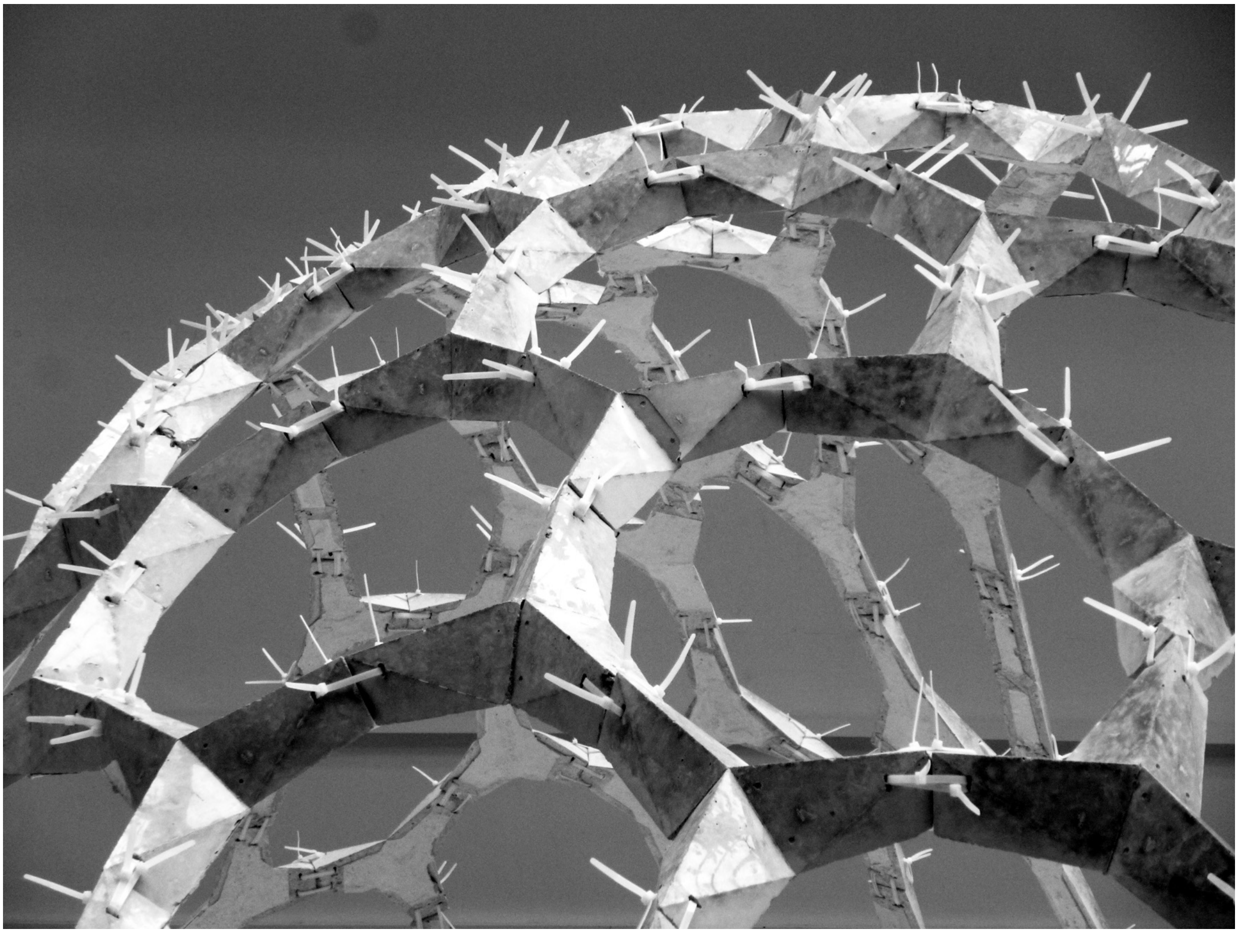
Figure 4: Concrete tectonics diagram, exemplified with the ReVault case study.

plastic. On the basis of this starting point, the relations between *form, material and technique* as a generator of the mould (figure 5 [D]) were explored in the case study 'Hello World', which both confirmed the feasibility of casting in laser cut, folded PETG and established the limitations in size which apply to it, because the weight of concrete deforms the moulds when they reach a certain size. This consideration lies between material and technique (figure 5 [1]).

In the ReVault case study, the relationship between technique and form (figure 5 [2]) as well as material and form (figure 5[3]) were considered once again, introducing the amorphous catenary vault, which both in terms of the compressive flow of forces and geometrical complexity suits concrete a material (figure 5 [3]). This may be described as a triangular (or hexagonal) mesh and translates into individual components, thus matching the technique (figure 5[2]).

We can conclude that the choice of a rigid but thin material as the mould has consequences for the relationship between material and technique (figure 5[1]). An aspect of the tectonic potentials of deformative casting is the fact that the weight of concrete generates the form, as described above. By introducing the PETG plastic, this quality was traded in favour of precision and in fact deformation became a problem, especially with larger moulds.

This had consequences for the *mould tectonics* (figure 5 [D]) because the avoidance of deformations in the moulds was made possible by digitally triangulating the surfaces and adding stabilizing flaps to the edges of the mould which introduced further structural strength and could be attached to a blueprint.



Concrete structures are tectonic when the material and technique have a significant impact on the initial idea about form, in such a way that the final structure can be said to be a consequence of material and technique.*

*includes concrete and mould materials

CHAPTER 14: CONCLUSIONS, SCOPE AND METHOD CRITIQUE

The conclusion is divided into three topics set forth to present and subsequently discuss the outcome, the nature and the scope of this research.
Firstly, the main conclusions are summarized. Secondly, a method critique is offered, and thirdly an account of scope of the research and suggestions for further research is proposed.

INITIAL CONCLUSIONS

Based on research into established writing on tectonics, several conclusions regarding tectonics were made which constitute a conceptual universe of tectonic thinking, which is useful in addressing the research questions. The thoughts of Gottfried Semper were found useful to provide a strategy for describing form as a result of *material considerations* and the *process of building*. Furthermore it was concluded that the ideas of *poetic construction* set forth by Kenneth Frampton was useful in initiating inquiries which interconnect a certain constructive logic and a casting technique and to suggest the constructive - hence architectural - perspectives of a particular casting technique.
The thoughts of Marco Frascari which suggest a reading of *details* as a creator of meaning were concluded to be able to help establish a progression in the case studies.
Furthermore, it was concluded that experiments carried out as research

through design with a focus on tectonics, have to be evaluated on the basis of aesthetics. This led to presentation of four arguments, set forth by cognitivist philosophers, which propose how aesthetics may be part of valid scientific reasoning. Among the conclusions drawn from these four arguments a key finding is that the experimental case study research should escape being a mere reduction to or confirmation of what we already know, but should attempt to present something new.

It was concluded that the Material-Technique-Form triangle would be of assistance in searching for new geometric forms in concrete, as it addresses the central preconditions for creation of form as well as relationships between the three. Furthermore, a categorization of relationships regarding the mould making and the actual making of geometric forms in concrete was proposed. The former was referred to as *mould tectonics*, the latter *concrete tectonics*.

Finally, it was concluded that in order to approach the research questions, which entail an understanding of *concrete tectonics*, the investigations and experiments would need to focus on *mould tectonics*, since the forms in concrete relies on the form of the mould in which it is cast.

The thesis concludes that the possibilities in the 'art of making' in the 21st century should take precedence in order to investigate how coherence between the architectural idea and finished building may be reintroduced. This was done through an introduction to the concepts of *'New Production Philosophy'*, *'Mass-customization,* and *Digital Tectonics*.

In terms of the New Production Philosophy, the design strategy *Cradle to Cradle* (CTC) and concurrent engineering were found to be relevant. The Cradle to Cradle strategy has an interesting view on materials as resources instead of waste, which has implications for their use as casting moulds. Concurrent engineering was found to be of relevance as it presents an approach to including

constraints of production processes into the conceptual design and vice-versa. Furthermore it was concluded that that the complex nature and foundational changes from project to project, also referred to as *peculiarities,* may be accommodated by montage-strategies which are able to demonstrate coherence between technique and form in an industrialised environment, and are potentially applicable to a mass-customized concrete architecture.
These observations led to the conclusion that digital modelling and simulation as a mode of representation could be beneficial in the case studies, as it is not limited to a particular fixed point of view that both geometry and manufacturing processes at the same time. It was, however also concluded that while simulation seems like a great tool for ensuring that the processes and parts is central, the method should be accompanied by traditional means of representation, such as drawing and physical modelling. It follows that the potential of incorporating computation are that structural performance can be simulated and that production work flows can interact and form a basis for the representations, given a productive dialogue between architect and engineer.

An examination of an example from the era of modernism and mass-production, the Sydney Opera House, concluded that a paradox arises as parts of the building have causal relationships resulting in what could be called a c*losed relationship* between material, technique and form. This kind of coherence was found between the concept, the ribs and their construction, and the cladding. Conclusively, the characteristic appearance of repetition and Euclidian geometry that is often visible in buildings made from concrete elements is absent in the shells of the Sydney Opera House. This enables the work to stand for 'itself' and not anything else. There are endless ways of interpreting it and it is up to the individual to form his or her own opinion, as is the case with other art forms, due to the multiple levels of interpretation found in the visible and understandable relationship between concept, form, material and construction.

To position the research in a contemporary context, several conclusions regarding concrete casting in general and individualized casting techniques in particular were made. It was concluded that the architectural potentials of in-situ cast concrete lies in its heaviness and three-dimensionality, but that lack of standards means that formwork and reinforcement is usually custom-made and that the construction of the formwork is complicated. Pre-fabricated concrete elements were concluded to have limitation in size, defined by restrictions in the production facility and in transportation. The ability to industrialize and control the production, however, led to the conclusion that the pre-casting principle seems more advanced and controllable in comparison with casting in place and thus the right topic of study for the research here. Furthermore it was concluded that pre-cast concrete in its current form is used exclusively for the mass production of repetitive elements, which limits the potentials for creating complex geometries.

With regards to state-of-the-art casting principles developed in research and practice, it was concluded that distinguishing between addition, subtraction, and transformation (A-S-T) was helpful as a tool to analyse potentials and challenges in the mould making techniques. This distinction supports the hypothesis that tectonics is a starting point for the development of new methods, in which case A-S-T can provide a means to analyse the advantages or disadvantages of using certain materials and techniques.

The most widely used principle in contemporary practice, it was concluded, is *addition*. Euclidian geometry which used to shape rectangular moulds, presenting a geometric restriction to the inherent amorphous nature of concrete itself.

Subtraction, on the other hand, was found to be the most widely used technique for casting complex and amorphous concrete. It was concluded that subtraction is done with either CNC milling or hot-wire cutting of Expanded Polystyrene (EPS). While CNC milling was found to be a slow process, hotwire cutting was not. Both techniques, however, were found to create a problematic surface finish. With hot-wire cutting resulting in linearity in one direction it was considered more restrictive, but on the other hand it was concluded that this may be used architecturally, which is the topic of the first case study, 'Kofta'. Furthermore this study showed that an analysis of the logics of the CNC tool path might introduce a restriction, reducing milling time and introducing implications for the form. This formed the basis for the case study 'Tool Path'. The problematic surface of cut EPS led to the investigation if EPS could be cast into complex shapes as opposed to cut. This was the focus of the case study 'Under Pressure'.

The generation of a casting mould by means of transformation was found with textile casting. This technique, which could be called 'deformation' was found to represent a lack of precision which could become problematic when several fabric cast members are connected, and in situations where fabric cast elements are to meet industrialized, rectilinear building components, such as windows and doors. It was concluded, however, that textile had strong tectonic implications, due to the coherence between the heavy concrete as a generator of geometric form in the flexible fabric. The principle of transformation should be investigated but in a more controllable manner: folding, which was the focus of the case studies 'Hello World', 'ReVault', and 'PlayVault'.

The study showed that spray-cast concrete on top of inflated membranes and 3D-printing of concrete are techniques with severe surface problems, which is why they were not addressed further in the case studies.

In general it was concluded that problems with the technique and material may be seen as gaps in the relationship between material, technique and form, which the case studies should address. That is: the *mould tectonic relationship*.

CASE STUDY CONCLUSIONS

The case study 'Kofta' demonstrated how coherence between form and construction can occur with individualized concrete elements. It showed that the ability to create curvature in one direction while maintaining linearity in the other and the ability to differentiate each concrete element was central for the development of the proposal. This allowed the hotwire cutting technique to give rise to at least three different design typologies and innumerable variations of these typologies, taking into consideration place, culture and function. The case did not, however address in detail, aspects concerning digital design of production as well as resource-optimisation. Also, the problems relating to the EPS surface were not addressed. This problem gave rise to the case study 'Under Pressure'.

In the case study 'Tool Path' experiments with CNC milling led to the conclusion that the logics of CNC milling could be used to create individualized concrete roof elements, in which the traces from the production were not only visible, but became an integral part of the constructive logics. This resulted in the re-design of traditional TT-beams in which skewing or bending of the mould geometry could be utilised in designing roofs according to contextual circumstances. Furthermore it was concluded that short milling time could be achieved, thus addressing a central problem currently present with CNC milled casting moulds.

Dealing with the surface problem, the case study 'Under Pressure' concluded that the casting of EPS under pressure against an adjustable membrane allows for amorphous concrete elements to be produced. Shortcomings in the built pressure chamber revealed that it is difficult to achieve a quality of EPS comparable to that found in industry, where steam is better distributed through the EPS. Through an evaluation of the tectonic implication of using EPS, the cause of existing obstacles in the use of EPS for concrete casting was identified, which initiated the development of a new technique. Controllability of the mould geometry was sustained while two improvements over existing EPS casting techniques were achieved: a shorter manufacturing cycle and an solution to the surface problem. While multiple, connecting castings, and a satisfactory surface was not achieved, the experiment did illustrate how tectonic evaluation of a material may give rise to new use of technology. It was concluded that further experimentation needs to take place in co-operation with engineers and the industry, in order to utilize the knowledge regarding the physics of EPS casting, to up-scale the experiment to a building scale and to further develop the flexible membrane.

The case study “Hello World” showed that parametric modelling can support the generation of concrete structures which can respond to complex material, conceptual and contextual relations. The parametric models are seen as a tool which enables a generative process, exploring boundaries rather than defining solutions. It was concluded that digitally defined parameters qualify the design if they are set up to define rules relating to concept, geometry / material, and fabrication. Specifically, a novel casting technique was developed using laser cutting and folding of large sheets of PETG plastic in which the ability to reuse the PETG moulds make the technique a zero waste production. This technique was used to cast and construct a sculpture consisting of three columns and four beams approximately 2,4 meters tall. The case study concluded that this use of material and technological preconditions form in the parametric model prevents the generation of arbitrary, digital representations which would translate into complicated and expensive manufacturing techniques. To enforce these tectonic qualities, a structuring of the script in *classes* and *objects* in order to keep track of the possible points of interference and development was proposed. Finally it was concluded that parametrically defined concrete elements cast using the applied technique can be both complex, accurate and have a high surface quality. Deformation of the PETG plastic, however, sets a limit as to what element size can be achieved if precision is to be maintained.

Building on conclusions drawn in the 'Hello World' case study, 'ReVault' was a refinement of the folded PETG casting technique which led to the development of a case study pavilion approximately nine by four meters.

Imposing restrictions to size and geometry turned out to be of high importance to be able to stabilise the mould during casting. Also, the meeting between components had to be simple. As such the system may be said to allow for a *ruled formal freedom*. As long as these rules are taken into consideration the proposed method allows for the design and fabrication of complex funicular structures from discrete precast concrete elements. It was concluded that feedback loops in the design process led to the development of strong tectonic relationships between material, technique, and form. In general, the pavilion demonstrated how the integration of digital form finding techniques, computational file-to-fabrication workflows and a sustainable concrete casting techniques can be used to construct complex funicular structures in a practical, affordable and materially efficient manner.

The last case study, 'PlayVault', was similar to 'ReVault', but more complex and constructed using a commercial fabrication facility as opposed to laboratory equipment. The study gave rise to conclusions regarding the design and manufacturing . Firstly, small design changes turned out to have a great impact on the performance of the pavilion. A decision to upscale the components resulted in greater deflection of the PETG mould which in turn decreased the precision of the elements. Improper fixation of base components caused the components to rotate away from the ideal position, which reduced the stability of the structure. In conclusion, the structure can be said to illustrate the limits of what the building principle can accommodate: small design changes and flaws have great consequences. Furthermore the PlayVault case study showed that the manufacturing is sufficiently simple to take outside the laboratory and into a commercial production line.

CONCLUSIONS REGARDING TECTONICS RELATIONSHIPS

Based on an analysis of the empirical and case studies, five properties essential to the mould material were defined: *a simple process*, *amorphous form*, *complex form*, *surface quality* and *precision*. A given mould material was found to often excel in one property at the expense of others. This led to the claim that subjecting the mould material to an assessment of the *tectonic logics* of the material is needed to deal with the possible restraints. However, a single concrete casting technique that was able to address all these problems, was not identified. Neither in state-of-the-art nor in the case studies. It follows that none of the case studies present themselves as 'the one casting technique to end them all'.

The attention to the relationship between Material-Technique-Form introduced as a conceptual framework, was confirmed to be pivotal in order to produce moulds which are tectonic. These mould tectonics relations were concluded to be the predecessor for dealing with the concrete tectonics relationship, that is: the nature of the creation of the elements should precede the development of construction and also influence architectural form. Put differently, mould tectonics is to be viewed as a means to achieve poetic constructions, as set forth in chapter two. The case studies 'Kofta', 'ReVault', (and to a lesser degree 'Hello World') all followed this logic, the design followed findings regarding mould material and technology. In this tectonic design strategy the mould making technique is elevated to become a design parameter, rather than a means to achieve an already established formal intention. The empirical studies and the case studies approach an exemplification of such bespoke relations between form, technique and mould, or in some cases, lack of a relationship between the three.

SCOPE

The creation of individualized architecture in concrete, when observed from the perspective of practices, is difficult. A few practices possess the competences to utilise new production facilities in the building designs. This points towards the development of techniques such as the ones presented in this project into *systems* or *chunks,* as described in chapter two, much in line with what is available today from the precast industry. The question remains if it is possible to define such systems in which the concrete elements fit into an industrialized production on a large scale, while being individualized and able to adapt to a multitude of different projects with different design criteria. The ReVault pavilion holds implications for how it might be done, notably the design to production logic is a case in point of how a simple input (a network of curves) is sufficient information for the generation of the entire structure.

It is my hope that the research presents the reader with knowledge of the field which may be helpful in pursuing a tectonic approach to actual building design. As such, application of this research in an architectural practice could happen by a tectonic evaluation of already gained experiences regarding materials and techniques. It is my hope that a reflection upon the findings of this research can be helpful in such a process.

The English Professor in Architectural History, Adrian Forty[1], notes that concrete has had a revival in the last twenty years as a reaction to post-modernism. The Swiss minimalist style is mentioned as an example of an architecture

1 Adrian Forty, *Concrete and Culture - A Material History* (Reaction Books Ltd, 2012), p. 280.

where the material is expressed, not hidden. Adrian Forty refers this minimalist approach to building with concrete to the critical regionalist attitude presented by Kenneth Frampton, in the sense that Swiss and similar architecture puts emphasis on un-treated surfaces and materials exposure.

In the light of this research it may be questioned whether these buildings are the right answer to the problem of post-modern eclecticism, as proposed by Forty, or to the repetitive international style of the modern period, which still prevail today. It may be argued that the geometrical form of buildings made in a minimalistic style is to a large extend the result of a formal approach of simple, Euclidian geometry, rather than a wish to express the geometrical complexity achievable in concrete. Further, the Swiss minimalist houses are made cast in-situ and therefore resource demanding and laborious to construct. As such they do not represent a viable alternative to the cheap production of repetitive concrete elements.

In the swiss building culture the notion of *concrete tectonics* may be of relevance in a sense that attention to the parameters which govern the creation could be added to the idea about form, which in turn will affect the use of both material (concrete) and technique (mould tectonics). Of course, built forms may be tectonic without serving as a response to an architectural programme, in which case they are closer to being pure art. This is true of the case studies, among which the case studies Kofta and PlayVault are perhaps the ones closest to being able to respond to an architectural programme, while Tool Path and Under Pressure are furthest from being able to do so. This is reflected in the description of tectonic relations, which do not deal with many of the circumstances imposed on the architectural process, such as building codes and economy. With reference to the discussion around art as presenting trivial knowledge introduced in chapter two, the case studies do not represent a mirror of reality, which gives rise to the question whether they are able to say something about reality. That is: are these somewhat simplistic examples sufficient to postulate a change in actual building practise? In response the work presented here can be said to inaugurate a specific line of *thought*, namely tectonic thinking and illustrate it with examples that reach beyond the boundaries of what is already known. As such, the case studies and the conclusions derived from them do not serve as a design manual with which concrete architecture of the future may be conceived, but rather as an inspiration to which approach one may take in order to put emphasis on tectonics when building in concrete. So while this research has investigated concrete with complex geometry and novel casting techniques, the tectonic approach could be applied within existing precast concrete building principles. Attention to the casting techniques could potentially add aesthetic quality to the elements produced, and the way they are assembled on site, a quality which could re-introduce concrete as a visible part of our build environment. This would require more than especially treated surfaces, but an upgrade to the precast building principle as a whole, exposing and exploding the geometrical preconditions and preconditions around the logics of assembly architecturally.

Further assessment of concrete's properties as a basis for conceiving concrete tectonic relations could include its composite nature when used with reinforcement; or its three-dimensionality and ability to transfer forces when cast in-situ; or the mixture of sand, stones and cement which make up the concrete. Altering the content of cement, for instance, results in either strong concrete or weak concrete, thus enabling a deliberate decay or degeneration of the built forms.

The research into the form and material relations eventually came to be about devising novel techniques for casting amorphous concrete elements, rather than utilising existing ones. Emphasis on technology in this regard was necessary in order to shift the focus from this technology towards material and form

– topics that both important matters when approaching architecture from a tectonic outset. As such the resources put into developing a new technique serves the purpose of realising potentials that lie between the concrete material and the mould material.

METHOD CRITIQUE

The research questions put forth as the research framework for this project can be said can be said to contain two areas of enquiry. The first part is empirical studies, presenting possibilities and obstacles in current concrete casting research and practice. The second part is a series of cast experiments, meant to contribute to the development of today's concrete production by exploring the tectonic potentials in mould making using the newest technologies.

In order to deal with both areas, three approaches to the research problem have been presented:

- A relationship to the conceptual framework of the project (primarily tectonics) was established.
- An empirical study and subsequent analyses was performed. The examples were selected to uncover possibilities and obstacles in current concrete technology, and the perspectives for tectonics.
- Six case studies, most of which were of an experimental nature, were designed to highlight some of the central features of the research problem.

The three approaches were laid down early in the project in order to facilitate my navigation around the research question and facilitate discussions, both during the project with advisors, and to help structure the thesis. Although the thesis has come to reflect the three approaches in a linear manner, development in all three areas has taken place simultaneously, based on an assumption that they will each have knowledge spin-offs of benefit to the other two.

In other words, the empirical studies were selected on the basis of an assumption that they would benefit the casting experiments, and vice versa.

The main reason for establishing tectonics as the conceptual framework was to ensure the project related to existing research regarding tectonics. This project is a part of the research project 'Towards a Sustainable Tectonic Building Culture', and thus needs to relate to the research taking place there.
The empirical studies were initiated as a means to gather knowledge of how current technology is applied in architecture, seen through tectonic spectacles. To my knowledge, no material has been written or collected on this.
As it is reflected in the chapter 'the Foundations of Concrete Tectonics', I have come to believe that tectonics involves aesthetics, art and 'architectural value'. In my opinion these are complex matters to address verbally, but clearer when discussed on the basis of presentation as opposed to representation. That is: through doing and making. I hope the production of concrete castings and the description of bespoke technique has made some things clearer.

As mentioned above three approaches to the project have been developed simultaneously. I could have chosen to adhere to a strict division. For example, I could have begun the study with an elaborate research into the 'fathers' of tectonics, such as Frampton and Semper, or go down a more philosophical road and undertake a critical study of Aristotle and Heidegger.
Ultimately I chose to do so because it could leave the obstacles/barriers of the present situation unaddressed. Retrospectively, however, the approach to tectonics can be said to fail to address the full richness of the term. A more thorough theoretical assessment might have aided the case studies. I hope that when seen alongside the results presented in the project 'Towards a Tectonic Sustainable Building Culture', a more comprehensive picture is drawn.

Another approach to the project would be to focus exclusively on empirical studies and to discuss how these do or do not utilize concrete in a way which lead to both increased architectural value and saving of resources. A number of current projects could be studied in detail: for example Mark West's textile castings in Canada, Karl Chritiansen's hot- wire-cut cutting technique, the 'Unikabeton' project, and state-of-the-art projects from practice. I suspect this would have ended up being just a commentary on existing research and works and thus not as focused as experimentation with several different techniques. By merely carrying out experiments and not undertaking empirical studies, I would lose the ties to existing discourse which I regard as important in justifying the relationship with current and future research.

Admittedly it has been difficult to decide on which case studies to carry out, which ideas for case studies to scrap, and how far to take each case. Potential cases have been dismissed on the basis of a non-scientific and tacit selection process, a gut feeling of whether a given case would benefit the other cases or the project in a different direction. 'Under Pressure', for example, had to be stopped before it grew into a disproportionate, technocratic exercise of designing pistons and controlling steam.

Several case studies call for a bespoke architectural expression, and represent only to a lesser extend a generalised casting technique which could be utilised in architecture. In general, this is a problem for recent projects investigating digital design to production. The research projects which are realised are either cardboard models or small scale research pavilions or 'demonstrators', similar in scale to the ReVault pavilion.

Put differently, this research does not represent elaborated concrete casting systems which provide answers to tectonic concrete construction ready to implement in practice. This is a consequence of the narrow use of tectonics set forth in chapter two and the experimental nature of the case studies which leaves general questions regarding tectonics and building culture unaddressed, which may be seen as a weakness of the research. It has been a true challenge to refrain from digging deeper into all of the interesting problem areas under each of the three focus areas, keeping each one of them from assuming the magnitude of entire Ph.D. projects of their own.

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