# Folding in Research

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**Abstract**

The paper describes how the research collaboration between design faculty and the research arm of one of the world's largest concrete and cement manufacturers can serve as a basis for advanced building technology courses and provide internship opportunities for the students to further deepen the knowledge they gained in the class. The larger context of the course is the recent advancement in concrete mix technology and the resulting opportunities to develop novel fabrication and construction techniques.

The paper showcases a professional elective course (seminar) that was structured around an advanced concrete cast technology that allows concrete forms to be poured onto flat formwork that is wet-folded into its final form, reducing the need for complicated formwork to achieve more geometrically complex concrete elements. After the seminar concluded, one of the students had the opportunity to further assist and develop the project during the summer as an intern at the research and development lab of the concrete company that provided the mix for the class.

In an effort to showcase a lineage between course work and student internships, the paper focuses on one of the projects that used the approximation of a shell structure through a folded triangulation (coined 'creased shell'). The geometry was developed and tested in collaboration with the faculty and further developed in collaboration with the industry partner. The results of that project became a key component of the overall research work the course was embedded in. Therefore, the paper will reflect, in the context of such research projects, a collaboration between the material industry and the academy that can offer valuable opportunities for students to gain access to advanced material research through hands-on experience.

This paper showcases how material technology can foster new design strategies where architectural form emerges from a understanding of material properties and processes.

## Background

*Research Collaboration*

The seminar course is part of a larger research collaboration between the professor and his colleague and one of the largest cement and building material manufacturers in the world. This multi-year collaboration has originated from a research lab visit during a study abroad travel course that focused on the intersection of material culture and architecture and has since evolved into a collaboration based on bringing together the architectural design expertise of the professor, his colleague, and the material and technical knowledge of the manufacturer. The broader context of the collaboration is the evaluation of the rapid changes in concrete technologies over the last decade and its possible impact on future architectural applications, in terms of form, tectonics and new construction methods. But it is also an opportunity to combine design research agendas with pedagogical aims; both academically as well as from the role of the manufacturer. The manufacturer is interested in giving future generations of professionals an insight into the mechanisms that form the interaction between the construction and material industry's latest developments and how it impacts design.

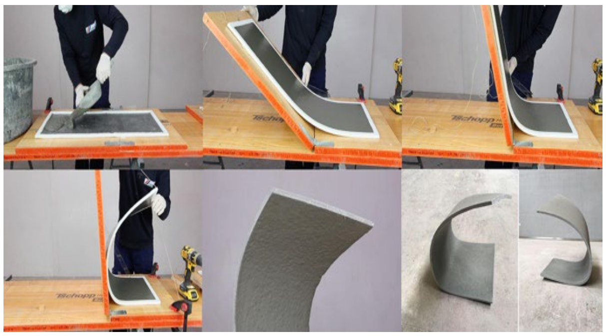

*Fig. 1. Demonstration of the basic folding principle.*

Advancement in Concrete Mix Technology

The potential impact on design starts with a novel concrete casting technique called 'wet-folding'. Concrete, as a composite material, has a long history of constant improvement of its matter through the reconfiguration of its mix.[1] It is the mix that forms a kind of base matter that has formal and performative qualities embedded within it. And it is the mold that materializes this matter.[2] The 'wet-folding' technique rethinks the mold through folding high strength concrete mixes from flat casts into complex spatial geometries before the mix has cured (*Fig. 1)*. The technique is made possible by a series of innovations that lay in the design of the concrete mix. This includes the use of proprietary high-performance concrete mix designs in combination with precise calibrations between the viscosity of the mix, the acceleration of the curing process and the use of reinforcement fibers.[3] Although the mix design is a crucial component of the success of the casts, the scope of the paper extends beyond the technology behind the mix to speculate on ways to fabricate formwork and what types of forms can emerge from the process. In the context of a professional elective, the mix technology was a starting point to explore novel ideas of formwork; from folding to bending, to popping, to rotating. The student work is, therefore, situated in the realm of design research and was evaluated on the basis of empirical requirements of the mix and what can be achieved with common materials for the formwork as well as aesthetic and formal results.

*Advancement in the Relation Between Form and Formwork*

To translate from traditional concrete and common formwork to more advanced methods, the students started with a basic understanding of concrete mixes. Traditional formwork has always reflected the negative of the form a designer intends to make; thus complex geometries are dependent on the production of complex formwork. In most cases, this suggests that for each different form made, specific molds have to be manufactured to fit that particular form. While it is possible to cast multiple pieces from the same mold, most often the formwork cannot be altered to cast a variety of similar pieces that change in scale, proportion, etc. The result of making varied forms is an expensive and complicated production of custom-made molds. This is typically avoided, especially in the pre-casting processes, where economy depends on maximizing the output of pieces per mold. Thus, being able to disconnect the form of the formwork from the form of one specific cast has long been a key focus in the development of new concrete construction technologies. The most common solution to this problem is the use of modular formwork elements, such as the PERI System that serves as a basis that is expanded upon with project specific formwork alterations and inlays that are typically used for in-situ construction or complex steel formwork prefabrication that are typically used for high volume production of architectural elements, such as t-beam, columns and stairs. But the formal variety of these systems are very limited and are typically intended for standard construction.

Conversely, the above-mentioned advancements in concrete mix science, and the introduction of digital fabrication and construction over the last two decades have led to a series of different research projects that propose new modes of concrete construction. Gramazio Kohler's TailorCrete[4] project, for example, proposes wax cast formworks that allow for complex curved geometries to be cast with the help of industrial wax inlays that can be re-melted. Or with Fabric Forms, they use a robotic controlled fabric formwork that was developed at UCLA by Sarafian and Culver,[5] to control the final form with less traditional formwork techniques. And there are many different concrete 3D printing projects, such as the RRRolling Stones from HANNAH,[6] to develop a process of making that generates new formal expressions with 3D printing. All these projects take advantage of the changes in mix design and fabrication tools to redefine the relationship between mix, mold and technology.

Similarly, the wet-folding technique also challenges the typical idea of the concrete mold and proposes a concrete that is no longer a heavy and thick material with only great compressive strength but lacks in resisting tensile forces. Contrary, this new concrete mix material has the capability of being thin, light and flexural strength that are typically more closely related to the properties of steel.[7] As these developments challenge the understanding of concrete as it is typically used in construction, advanced seminars offer an opportunity to expose students to these new developments and explore the potential for new formal investigations by collaborating with the material industry.

*Exposing students to Industry*

Over the last two decades, considerable changes occurred in material science and fabrication that continually find their way into the production of architecture. The research on the implementation of these technologies into everyday architectural production are still predominantly driven by research institutions, startup design firms and entrepreneurs, rather than by established architectural practices.[8] Experiments in materiality often involve innovative approaches to design computation and digital fabrication, and now increasingly rely on interdisciplinary teams of designers and scientists.[9] This new mode of operation will be a fundamental part of the future that current students will encounter in their career. To better understand this future, it is important for students to work with technologies and materials as a hands-on experience and participate in material research that explores what these technologies have to offer. To advance student's knowledge in materials, the study of new techniques in collaboration with the material industry provides exposure to a range of innovative projects that could inspire the design process. Even though it is challenging to integrate such experiences in large lecture courses; professional electives offer an opening in the curriculum to fold pedagogical goals into design research agendas. The open-endedness of the content allows for empirical as well as speculative explorations that are difficult to fit into the framework of other core courses. And the seminars allow, by their very nature, to narrow the scope of investigation so that it is possible to dove tail the course into larger research projects. Which, in the case, the course led to the opportunity for one of the students to further expand the work done in the academic context to the research lab of the manufacturer.

## Course Framework

*General Structure*

The course was divided into two concurrent sections: 'theoretical' and 'practical'. Most of the 'theoretical' content was frontloaded, so that the students had a better understanding of the cultural context of the material and acquired specific technical knowledge needed to productively engage the material. While there is no clear delineation between one and the other, the course is structured so that, towards the end of the semester, the students focused on lab time to dedicate to the iterative production of formwork and casting concrete.

The place of origin for the ‘theoretical’ section was a series of lectures, readings and case studies. The lectures expanded on the basic knowledge that students have of concrete construction. To provide the students with a more sophisticated understanding of what concrete is, the lectures looked at both the history of the material as well as at its current development and possible futures. Readings, such as Mud and Modernity from Adrian Forty’s book Concrete and Culture[10], or Thomas Schröpfer’s essay ‘The Alternative Approach – Observation, Speculation, Experimentation’[11] helped the students understand that the research they participate in is not simply focused on technology but strives to operate between the technological development of the material and its congruent cultural implications. This was further emphasized by asking the students to prepare presentations that explained the work of architects, such as Felix Candela and Miguel Fisac[12]. In the work of both of these architects there is a very strong connection between structure, form and modes of construction, tied to economy and social concerns and ideas. In contrast to the discursive nature of the ‘theoretical’ aspect of the course ‘practical’ section of the seminar was dedicated to the design of a small canopy through exploration of different wet-folding techniques. Reversing the typical design methodology, the students did not design the geometry or the form of their canopy first and then seek to resolve its construction, but rather the design emerged from studying the potentials of a construction and fabrication process. Based on this logic the students were asked to directly work with the material itself and speculate on its potential through their own empirical conclusions and not through referencing literature.

*Learning Goals*

The learning goals of this course were three-fold. First, the course was intended for students to get a better understanding of contemporary concrete construction. This was accomplished through lectures but also through their hands-on experience, which illustrated that concrete is no longer a heavy, thick material that they typically imagined of concrete. Rather students began to see, as so many other advanced materials can accomplish, that this new concrete material has a wide variety of different uses, performances, fabrication and construction methods with broad architectural uses and expressions. Looking at precedent and working through their own projects, they learned how the recent changes in concrete construction have broader implications on architecture as a whole. This might be a very obvious observation, but it is through combining design research and fabrication with broader design ideas that the students truly started to understand the connection between technological advancements and architectural design. Second, through the development and fabrication of the formwork and casting, the students learned what it means to understand and use construction as part of design research. Answering questions on how you have to construct a formwork for it to operate in an intended way, and how the construction of the formwork relates to the concrete mix are not questions that are only relevant for their specific projects, but are important lessons to understand how engaging with technical questions can advance formal ambitions.

Lastly, and perhaps most importantly, the course allowed students to get an insight into how exploring new materials and fabrication techniques can be the basis of an architectural design process. Working with the actual material, the students were asked to simultaneously develop possible fabrication and construction processes and speculated on the potential structural applications, combining hands-on material explorations with digital design and structural analysis tools. A process that foregrounds design research with a foundation in processes and technical knowhow, the students were provided with the capacity to engage the construction industry not just as a consumer, but as an active participant that helps shape its future.

## Methodologies (through samples)

*From Folds to Folding*

The students were asked to develop a small-scale canopy by using a fabrication technique that would be based on 'wet-folding' concrete. To further explore their proposed technique the were asked to build digital models that showcased how their technique could scale up and be imagined as structural system at an architectural scale, building on structural ideas, formal expressions or means of construction that they observed in the work of the architect they presented earlier in the semester. While there were different approaches regarding the use of the folding technique, this paper focuses on one student project that aimed to develop a 'creased shell'. Especially since this project was further

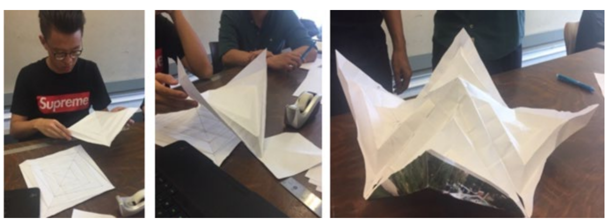

*Fig. 2. Initial paper model studies.*

developed over the following summer as part of the overall research project and allowed students to see the translation from small-scale material studies to a larger-scale version developed in the context of the concrete manufacture's professional construction research lab.

Being fascinated by the shell architecture of Felix Candela, this project started with the student's research on origami techniques in paper that allow to develop 'shell-like' forms. Using paper models that were based on single sheets,[13] the student approximated a series of different shell-like forms through different folding patterns (*Fig. 2)*. One of the main concerns was that the chosen folding pattern would allow for the folding to be possible without having folds that would be steeper than 90 degrees, otherwise the mix would slip off the formwork. In addition, the folding pattern should allow for the formwork to be easily foldable under the weight of the concrete with minimal movement and displacement since any unnecessary movement increases the chances that the mix will be overly agitated; increasing its slump and then sliding off the formwork.

Considering these concerns, a pattern was chosen that allowed the form to be generated with just pushing two opposite corners towards each other. While this effect is a result of the geometry of the folds, it was further enhanced by creating some 'valley' folds through scores on the one side of the material and the 'peak' folds on the other. While this proved to be simple in the paper model, the question was whether this system of folding could be scaled up with similar techniques using less malleable formwork. In other words, could the paper studies be translated into a formwork that can be operated on according to the same principals; even when under the weight of the concrete.

*From Folding to Formwork*

To transform the paper models into actual formwork, the translation of the folding mechanism was critical in the construction process. Initial models tried to replicate the folds in cardboard but the weight of the concrete required a stronger material, even at a small scale (*Fig. 3)*. The next version of the formwork was constructed from two

*Fig. 3. First simple cardboard formwork and cast.*

layers of laser cut wood pieces that were connected through a cloth glued between them. While this worked to fabricate a first successful cast, the issue was that there was no front and back side to the formwork that would differentiate between the 'peak' and 'valley' folds.

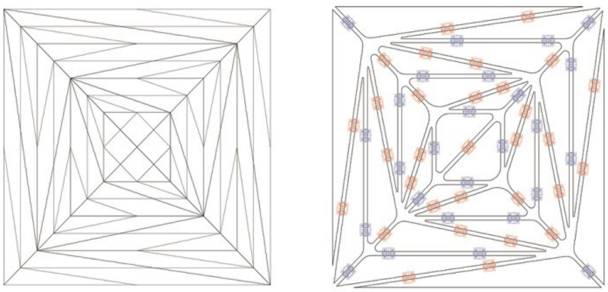

*Fig. 4. Redesign of Geometry into hinged formwork (colored hinges indicate valley or mountain fold).*

This made the operation of the formwork, at a larger scale impossible, since it lost its ability to fold by just pushing in the corners and needed more manual adjustment. This change, in turn, reactivated the mix and caused slumping. This increase in slumping created inconsistencies in the thickness of the concrete as well as a lack of precise edges and clean lines in the form.

To eliminate these issues, the scale of the test was increased so that the folds could be replicated through a series of hinges between the wooden pieces (*Fig. 4)*. The position of the hinges on one or the other side of the formwork allowed the differentiation between 'valley' and 'peak' folds. To ensure that the mix would not be caught in the folds, a plastic sheet was used as an underlay before pouring the concrete. This helped eliminate some friction that occurred between the formwork and the already cured concrete but the resulting surface quality closely resembled the ripples and folds in the plastic which was not a desired outcome. But the techniques were a success in that the form could move and adjust the way the student anticipated. This setup allowed for a series of initial casts and formed a clear conclusion for the context of the course (*Fig. 5)*.

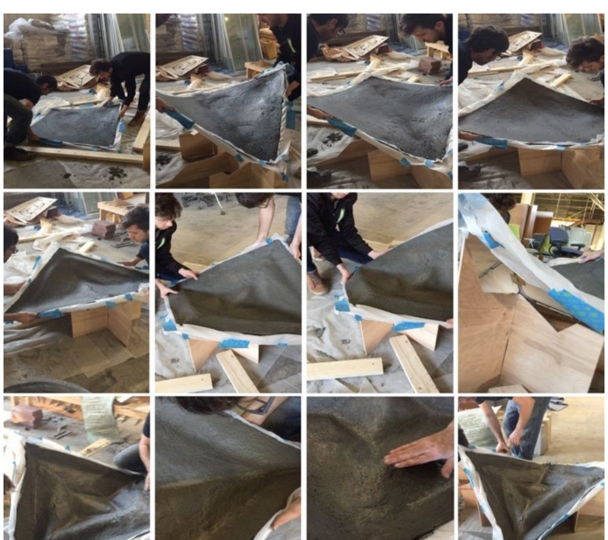

*Fig. 5. Folding of "creased shell" at intermediate scale.*

*Analysis*

With the support of an engineering faculty member, the student translated the geometry of the shell-like form into SAP2000. Since the chosen geometry was more complex than a traditional shell, and that the casts were small in scale, the analysis was not intended to provide true feedback since there were many unknowns as to the slight variations of surface angle with the creasing angles of the surface. But this process allowed the students to get an insight into a research processes that combine physical investigations and digital analysis. And while the scope of the course did not allow for a direct feedback loop, the analysis confirmed the need for additional material strength in the folds.

## Results

*Course*

The pedagogical result was perhaps best described in the one student's response to the course:

*"I was very happy that I was able to learn more about the historical context and various usages of concrete. But above all, designing something out of a new material was*

*‘cool’ and interesting. Dynamics between actual construction, advanced research phases in an industry’s research lab, and course efforts to stitch the gap through design (research) really excited me.”*

The main research result showed that the small-scale tests could be scaled up with a similar fabrication method (*Fig. 6)*. Especially since the models proved that an increase in scale actually helped to ease the fabrication and demolding process, since the ratio between the gaps needed between the pieces for the folds and the bending angle of the pieces were easier to control, resulting in a clearer articulation of the form.

*Fig. 6. Final form of student ‘creased shell’ prototype*

Internship

Given the successful tests that were done in the context of the course at the University, we decided, with our industry partner, to explore this technique in more detail at a larger scale. This resulted in one of the students having the opportunity to further develop the ‘creased shell’ project as part of a summer internship at the manufacturer’s research lab. The student worked under the supervision of the professor but was part of the technical fabrication team of the manufacturer.

The major challenge when scaling up the formwork lied in the translation of the hinges into a system that would work when it is operated by a crane due to it no longer

*Fig. 7. Crane lift at Manufacturer Lab, done by student in collaboration with technical staff of manufacturer*

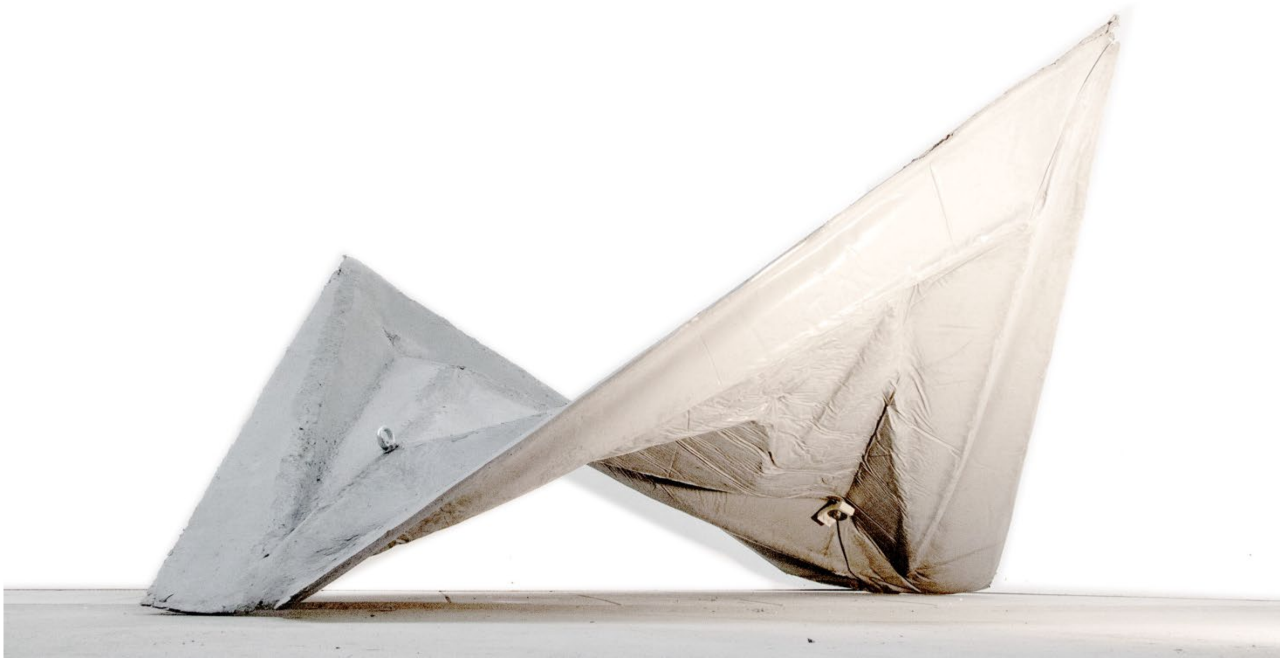

*Fig. 8. Scaled-Up version of 'Creased Shell'*

being possible to manually manipulate the formwork. But in essence the formwork was able to be fabricated at the larger scale in a very similar manner to the smaller iterations. The angled surfaces, to comprise the ‘peaks’ and ‘valleys,’ were CNC routed wood pieces glued with epoxy to a malleable fabric surface. The original fabric was replaced with a geotextile fabric and the hinges were translated into a series of metal strips that were connected either at the bottom or top side of the formwork.

To manipulate the formwork at the larger scale, the movement of the formwork was translated into a series of cables that were pulled up by a crane. In the smaller scaled version, the digital design process was useful to generate the cut sheets for the formwork and preview the general movement of the formwork from its flat to folded state. But in the larger version, the movement of the hoisting points in space where of great importance for the success of the cast. Therefore, a more refined digital model was constructed that traced the points and translated them into hoisting anchor positions and cable lengths that allowed the crane to operate fluidly with the formwork (*Fig. 7)*.

The final cast, at the larger scale of two-meters, was successful in providing a proof of concept of the technique (*Fig. 8)*. It also demonstrated that the increased strength of the mix generated structural forms that, with most standard concrete mixes, would not be able to be cast. Simultaneously the process of scaling up the formwork revealed the limitations of the functioning of the formwork system at larger scales due to the combined weight of the formwork and mix. These observations provided the research team with initial empirical proof that substantiated further discussion to expand the development of the research; enforcing an initial assumption that further explorations of the system might be best situated in the context of prefabrication, where the dimensions and weight remain in a manageable relation.

Conclusion

Given the rapid development of materials as well as construction methods in architecture, it is important to offer students learning opportunities at the intersection of design, fabrication, construction and material science. It is central to architecture that students learn to understand how they can productively act within this fast-changing context, ask the right questions and be responsible designers.

Seminar courses are a great opportunity to embrace new materials and methods in the design process as a form of research for students. Through providing the students with a hands-on insight into the industry, they are able to garner more specific knowledge and know-how than they typically receive from larger technology lecture courses. But to ensure that the students are able to contribute to the research in a meaningful way, it is important that they understand the larger context in which they participate in and be given the access and tools needed to engage in material research in order to have more impact later on in the profession.

Notes:

[1] For an abbreviated overview of the development of Concrete in the 20iest Century see Jester, Thomas C. “Part II – Concrete”. 2014. *Twentieth-century building materials: history and conservation*. Los Angeles : Getty Conservation Institute 2014.

[2] Réjean Legaut in Collins, Peter, Concrete: the Vision of a New Architecture (Montréal: McGill-Queen's University Press, 2014), XXXV.

[3] For an abbreviated overview of the recent development of high performance concrete mix design in relationship to architecture see Peck, Martin. 2017. ***Modern concrete construction manual: structural design, material properties, sustainability***. Peck, Martin. “Building Material and Products”. *Modern Concrete Construction Manual : Structural Design, Material Properties, Sustainability*. DETAIL Manual. München: DETAIL, 2014. 36-41

[4] Gramazio, Fabio, Matthias Kohler, and Jan Willmann. 2014. “TailorCrete”, inThe robotic touch: how robots change architecture : Gramazio & Kohler, Research ETH Zurich 2005-2013.

[5] Culver, Ronald and Sarafian, Joseph. 2017. “Robotic Formwork in the MARS Pavilion: Towards The Creation Of Programmable Matter.” ACADIA 2017 | Disciplines + Disruption, 522.

[6] "FOLLY / FUNCTION: ‘RRRolling Stones’." Http://www.architectmagazine.com. December 10, 2018. Accessed February 2019. https://www.architectmagazine.com/project-gallery/rrrolling-stones_o.

[7] Portland Cement Association. “Ultra-High Performance Concrete (UHPC), is also known as reactive powder concrete (RPC). The material is typically formulated by combining portland cement, supplementary cementitious materials, reactive powders, limestone and or quartz flour, fine sand, high-range water reducers, and water. The material can be formulated to provide compressive strengths in excess of 29,000 pounds per square inch (psi) (200 MPa). The use of fine materials for the matrix also provides a dense, smooth surface valued for its aesthetics and ability to closely transfer form details to the hardened surface. When combined with metal, synthetic or organic fibers it can achieve flexural strengths up to 7,000 psi (48 MPa) or greater.” Quoted from: “Ultra High Performance Concrete.” Cement.org https://www.cement.org/learn/concrete-technology/concrete-design-production/ultra-high-performance-concrete (accessed April, 2009)

[8] Fabricate, Fabio Gramazio, Matthias Kohler, and Silke Langenberg, ed., Fabricate negotiating design & making, (Zurich: Gta-Verlag, 2014), 6.

[9] Bechthold, M. & Weaver, J. C. Materials science and architecture. *Nat. Rev. Mater*. **2**, 17082. 2017.
[10] Forty, Adrian. “Mud and Modernity”. *Concrete and culture: a material history*. London: Reaktion Books. 2016.

[11] Schröpfer, Thomas. “The Alternative Approach – Observation, Speculation, Experimentation”. *Material design informing architecture by materiality*. Basel: Birkhäuser. 2011.

[12] As a reference the students were given the following two resources:

- Faber, Colin, and Felix Candela. *Candela, the shell builder*. New York, NY: Reinhold Publ. 1965.
- Asensio-Wandosell, Carlos, ed. *Miguel fisac & alejandro de la sota - parallel visions*. Madrid: La Fabrica. 2014.

[13] Jackson, Paul. Folding techniques for designers: from sheet to form. London : Laurence King Publishing. 2016.