THE PRODUCTION OF FREE FORMED CONCRETE ELEMENTS IN A FLEXIBLE MOULD

Maurice DOMINICUS [1], Joris KETELAARS [1], Paul VAN LAERHOVEN [1], Arno PRONK [2]

[1] *Student, Faculty of Building Technology, Eindhoven University of Technology, The Netherlands*

[2] *Assistant Professor, Faculty of Building Technology, Eindhoven University of Technology, The Netherlands*

E-mail: m.m.t.dominicus@student.tue.nl j.ketelaars@student.tue.nl
p.f.c.v.laerhoven@student.tue.nl a.d.c.pronk@bwk.tue.nl

KEYWORDS

bone structure, fiber reinforced concrete, flexible moulds, free form architecture, membranes, new production methods.

ABSTRACT

Evolution has proven that the microscopic geometry of the human bone (figure 1) is able to bear weights and at the same time to be light in weight. This quality, in combination with the attractive image of it, gave us a new field of interest for using this kind of morphology in a façade element. This type of element – free form - is an example of the forms that are pursued more frequently by contemporary architects. The growing interest for these free formed elements sparks the need for new approaches to production processes.

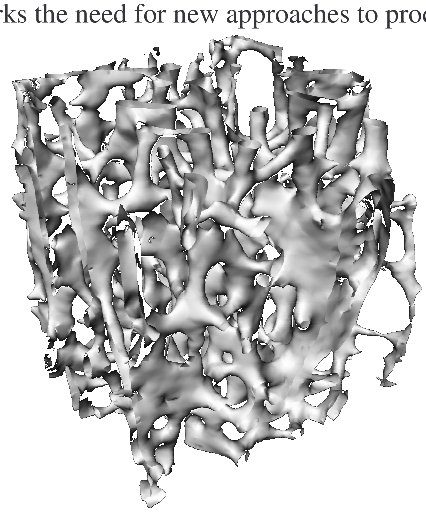

Figure 1. CT Scan of human bone at a microscopic level.

Figure 2. The final mockup

The approach of the production process of free formed concrete elements has usually been influenced by the traditional method of casting concrete into stiff moulds. In most cases this has lead to very complex and labor intensive production processes resulting into rather irregular concrete surfaces. In this project a different approach towards casting concrete has been chosen to develop a less complex production method that moreover, results into smoother surfaces.
To achieve this goal a mould has been made out of EPDM rubber. Sheets of this material were locally pressed together with wooden discs. In the process of casting concrete the elasticity of the material under influence of the concrete pressure leads to deflections. By being able to control these deflections up to a certain level, it is possible to produce elements that resemble the microscopic bone structure up to a satisfying level.

The research that has been done has lead to a mockup of a façade element out of fiber reinforced concrete (figure 2). In this particular project a model resembling a bone structure was chosen, however the production process enables several forms and patterns resulting in double curved and smooth surfaces.

INTRODUCTION

The growing interest in free formed structures in contemporary architecture conflicts with the traditional casting processes of concrete. The desire to combine the physical and structural qualities of this material with the esthetical qualities of free formed architecture sparks researchers to strive for new methods to produce these types of elements with concrete.
Georg Zimmermann from University of Kassel, Germany is exploring the structural and geometrical potential of Ultra High Performance Concrete (UHPC). This has lead to structures that closely resemble bone structures, as can be seen from the image in Figure 3. These elements are all planar and relatively small. Therefore they can be produced in specifically engineered and produced foam formwork. In essence this method is similar to the traditional casting process in which a negative stiff mould is filled with concrete.

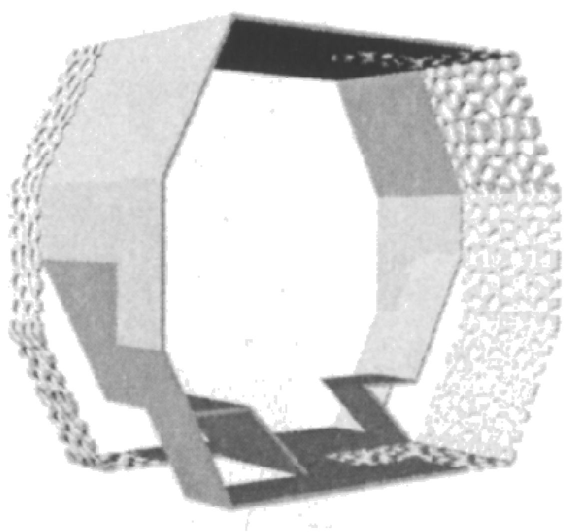

Figure 3: Pavillion out of UHPC (G. Zimmermann)[2]

Mark West from C.A.S.T. (Centre for Architectural Structures and Technology) and the University of Manitoba, Canada has taken a different approach for producing free formed concrete structures. By making moulds out of membranes that deflect under the weight of wet concrete new opportunities arise for engineering and construction technology and a completely new vocabulary in architectural expression can be developed. The deflection of the material under gravity results in structurally efficient variable section members. This reduces the dead weight of the elements and saves material expenses. In Figure 4 an example of this method can be seen in which a load bearing column is produced. This work has been an important inspiration in our search for a method to produce a bone structure.

Figure 4: Fabric column formwork awaiting concrete placement (left) and column after cast [3]

These developments in production techniques are in harmony with the rising interest in free formed architecture. To lower the barrier for such elements to be applied in buildings it is important to let the thought go of production complexities and to lower the production costs. More value can be added when the concrete is used as both an architectural as well as a structural element. In nature bone structures are used to build skeletons. It is able to bear the weight of the human body and at the same time is relatively light. This property has been an interesting starting point for making a technology transfer from nature to architecture by building a concrete bone structure that functions as load bearing as well as a space dividing element with a distinguished architectural expression.

HUMAN BONE

In figure 5 a section of a human femur indicates the two different types of human bone. The outer zone of the bone is made out of cortinal or compact bone. This is formed by blood vessels and canaliculi and has a high density (85% - 95% volume density). The core of the bone is made out of the more porous trabecular or cancellous bone (5% - 60% volume density)[1]. In figure 6 the highly complex structure of struts and plates of this type of bone is shown at a microscopic level.

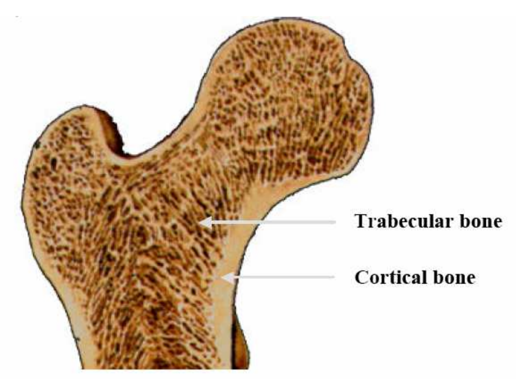

Figure 5: Section of human femur

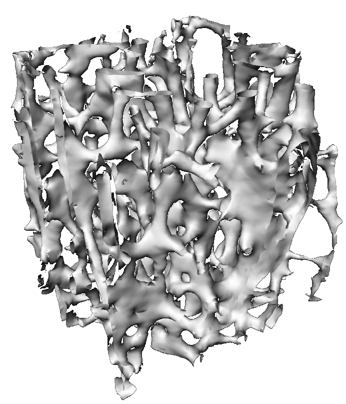

Figure 6: Microscopic section of trabecular bone

MODELING OF BONE TISSUE

In biomedical science human bone is subject of analysis. Two methods are used to generate virtual models of bone; scanning and virtual modeling and remodeling. In MRI-scans magnetic resonance is used to make planar images in different shades of grey. Each of these shades corresponds with a different value. These are used in a finite element analysis to generate virtual models that can be modified and analyzed. Figure 7 shows an example of a bone structure remodeled in FEA-software.

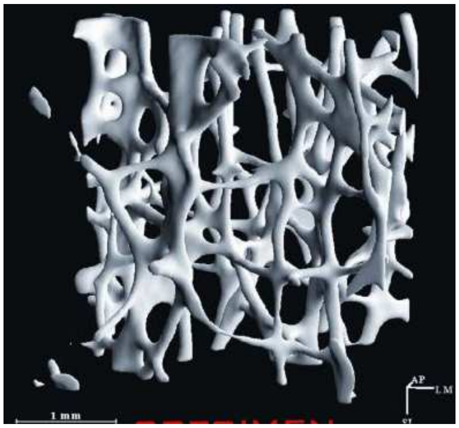

Figure 7: 3D-software to virtually rebuild a bone structure

Another way to create a virtual model is by starting with a porous initial configuration, as shown in Figure 8a. In an iterational process the structure is being remolded, depending on its behavior in response to impacts. This method is used to generate an approximation of the morphology. It gives insight in the way the structure responds to different impacts and the way it recovers. The structure is defined by the way it is being ballasted. When strong forces are applied to it, the structure will densify to be able to withstand the occurring tensions.

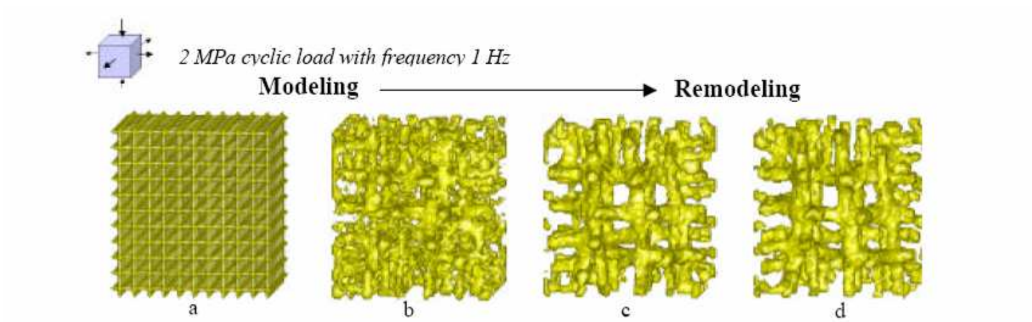

Figure 8: Process of forming the structure due to deformations[4]

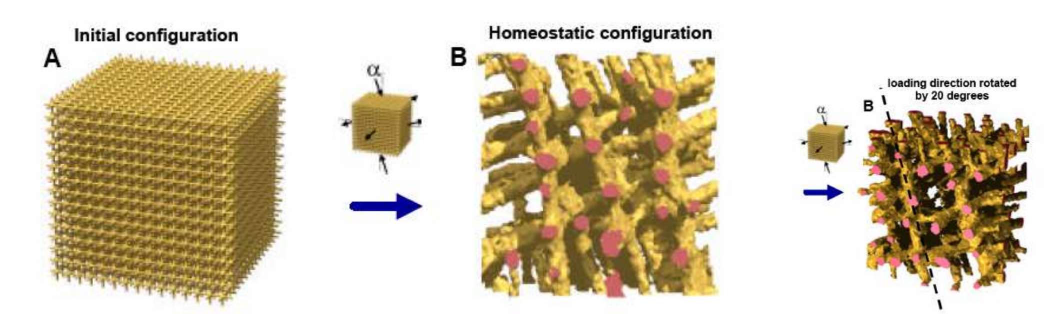

Figure 9: Process remodeling of a structure

Starting with a rigid initial configuration the bone is subject to the alternating forces. Young children have stronger bones than adults, because their bones have a much denser network of struts and plates. This also explains the quicker rate of recovery with children. A bone structure is generated in four to eight years, depending on biomechanical and external influences. In most cases, within eight years, the main struts and plates have been formed.

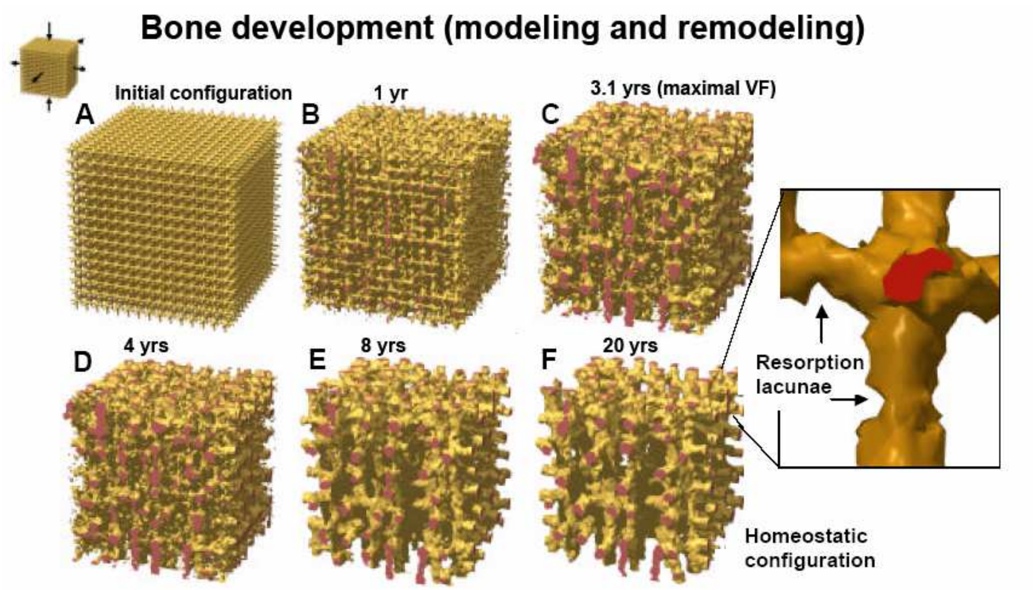

Figure 10: Process remodeling of a structure

Imperfections in bone-morphology can occur as a result of failure in biochemical processes. This will lead to a change in bone structure. A common bone disease under adults is osteoporosis which is a failure in the system that results in degeneration of the structure itself. The mass density (also known as Bone Mineral Density, BMD) will strongly decrease, as illustrated in Figure 11. Consequently, patients have a higher risk of fractures.
The bone-mass will increase the first 30 years after which the mass will gradually decrease. Full rehabilitation after a failure/fracture caused by osteoporosis is estimated between 20-50 percent, even after an operation, the bone is no longer able to generate itself. Osteoporosis is a growing problem in the health care.

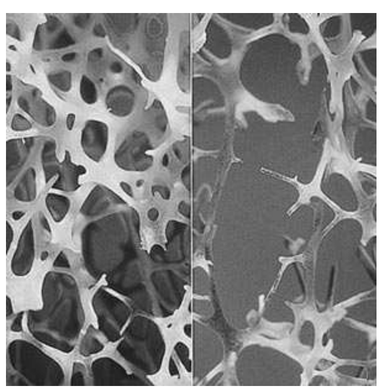

Figure 11: Comparison between normal bone and osteoporosis

The strength of bone is depending on its structure. Three types of loads can be distinguished that the structure is facing during its lifetime; tensile, compressive and shear forces. Figure 12 shows the mechanical properties of it. In the first stage, the linear elastic region, the bone will not deform. The next stage is the plastic region, in which the bone will break on microscopical level, causing little damage in the plates and struts. Total fractures will occur when the stress point is reached. The stress point is also known as the ultimate strength or the breaking strength. The bone will behave like steel after reaching its stress point. It will not break immediately, first it will deform until it finally collapses. Its mechanical behavior to long-term loads is similar to that of wood and plastics and is also known as creep.

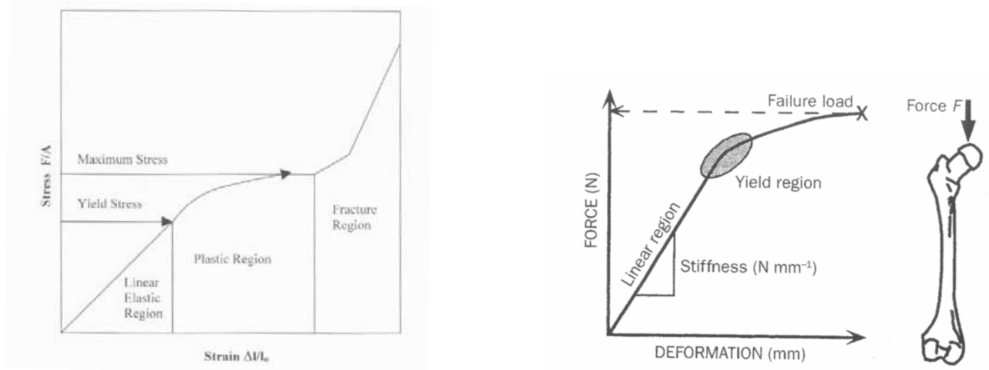

Figure 12: phases of mechanical properties

Bone can be mechanically analyzed in 3 or 4 point bending experiments, commonly used in testing concrete elements. Cortigal (1.1 – 9800 MPa) and cortical bone have a different Young's modulus. The highest value is measured at the top of the femur, the lowest at the clavicle. Variations in Young's modulus are less high in cortical bone; they vary between 5 to 28 MPa.

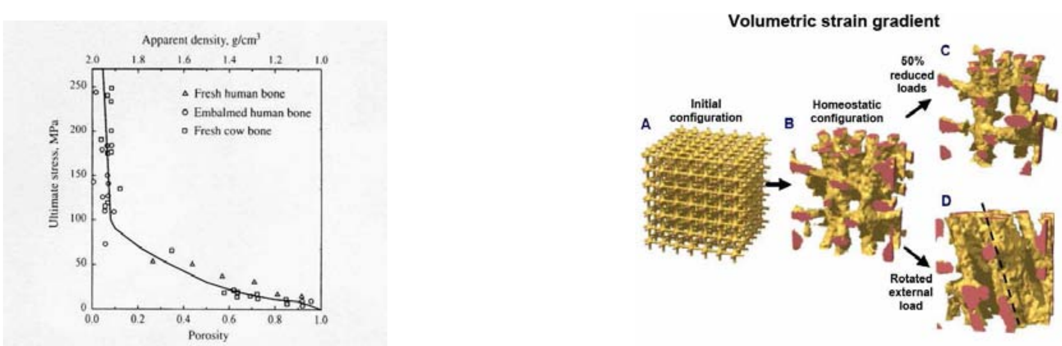

Figure 13: Conduct – stresses – deformations in structure

Polymer and aluminum foams have a structure that is comparable to bone, although they differ in density and regularity. Figure 14 shows a microscopic image of polymer foam.

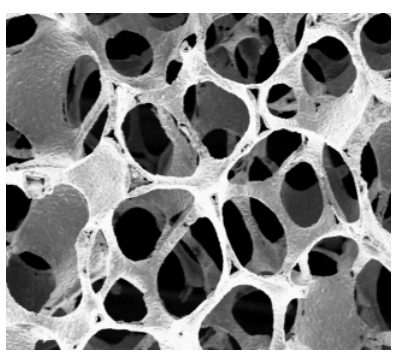

Figure 14: microscopical level of polymer foam

These structures have been used as an important inspiration and frame of reference in the design of China's National Swimming Centre by Herzog and De Meuron (Figure 15). This project shows that up-scaling of microscopic structures can lead to powerful architecture. Software enables designers to simplify such natural structures into building structures that are able to withstand forces.

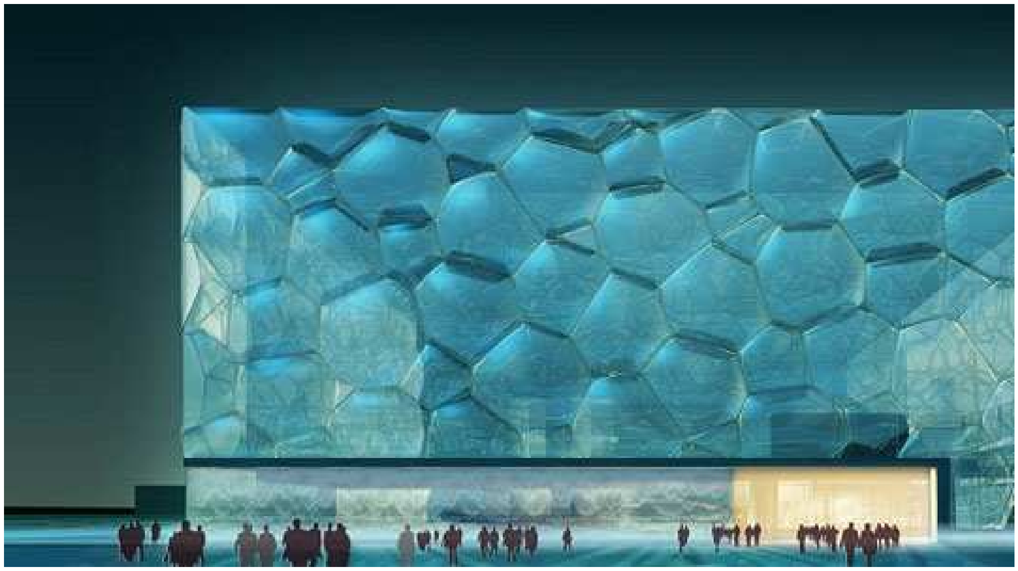

Figure 15: National Swimming Centre, Bejing, China (design: Herzog & De Meuron)

MOCK UP

The goal of this project was to create a free formed concrete façade element with a membrane mould based on a microscopic bone structure. Initially the attempt was made to achieve this form by using stiff membranes; welding a mold out of custom made patterns, however this proved undesirable because of the irregularities in the end-model because of the welds and the labor intensive process. Also because of the rigidness and inelastic characteristics of the mould the mock up was not fluent and curved enough. It would be possible to create a more fluent end model by increasing the number of patterns but this would prove to be far too difficult.
Another disadvantage of a welded and stiff mould was the fact that the mould itself was unrecoverable. In order to remove the mould it would have to be cut into pieces. Again this was undesirable for the fact that for each individual element another mould would have to be constructed. After some consideration it was decided to try creating a mould with two ongoing sheets of flexible material. This differs from the known processes to create a somewhat similar model casted in textile or Polystyrene moulds (reference 2, 3, 4).
After comparing some flexible rubber-like materials it was decided to use EPDM (ethylene propylene diene monomer rubber) known for it elastic characteristics. The material is used as a seal for multiple purposes but mainly as a roofing membrane. The slabs come in different thicknesses varying from 0.8 mm to about 2 mm and in 2 types. The American and European type which differs in elasticity and surface evenness. The American variation was chosen because of its smooth characteristics, leaving no imprints in the concrete.
The concrete used was a polypropylen-fiber reinforced concrete. The casting of the mould took place in an almost horizontal position due to the hydroscopic pressed of the concrete. This ensured the deflection and expansion of the EPDM-slabs at the base would not differ from the topside of the façade element.

Figure 16: Mould of façade element

As can be seen in Figure 16 wooden discs were used to define the lay out. At this point our method shows an important difference from that of both Zimmermann and West. They both use the primary casting material to achieve the desired form, where we achieve our form by modifying not the primary casting material (EPDM rubber) but its support (wooden discs). In this way we reduce the complexity of the production process and introduce a certain level of recoverability of the mould.

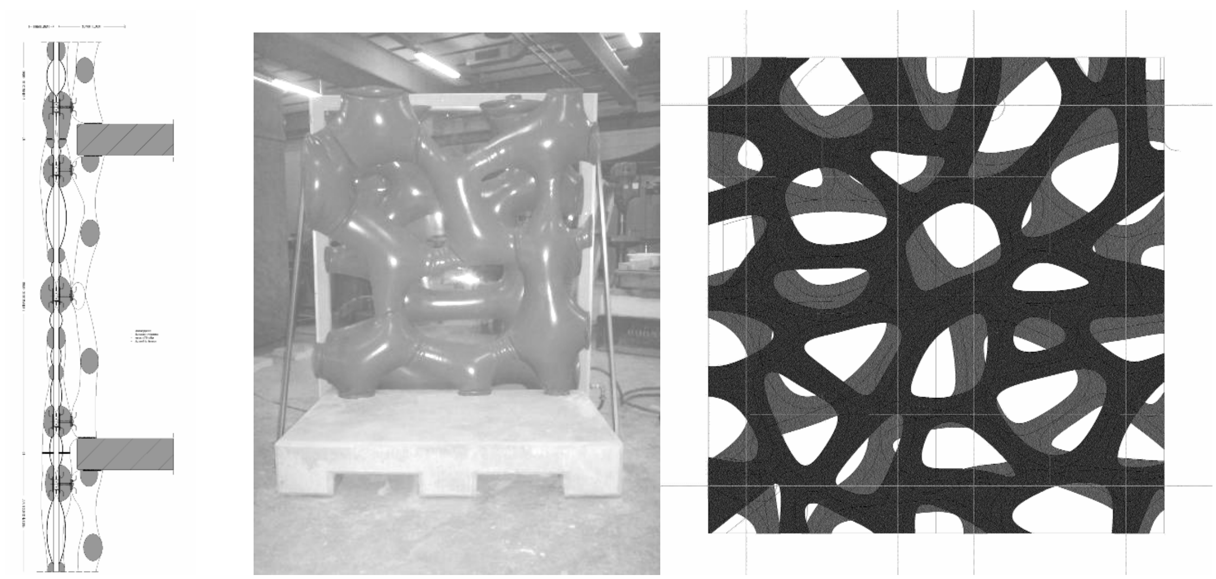

Figure 17: intersection, mock up, design layout

As can be seen from Figure 17 the façade element is divided into three separate sections. The inner layer functions as the bearing structure. Through a steel connection element, shown in Figure 18, a second half layer and a third half layer have been placed. Between these last two elements a cavity remains which functions as a thermal break that is filled with a transparent sheet that is pressurized.

This division increases its functionality in relation to the building process. The first element is placed during construction of the bearing structure, while the finite element is placed later in the process, when the façade is close.

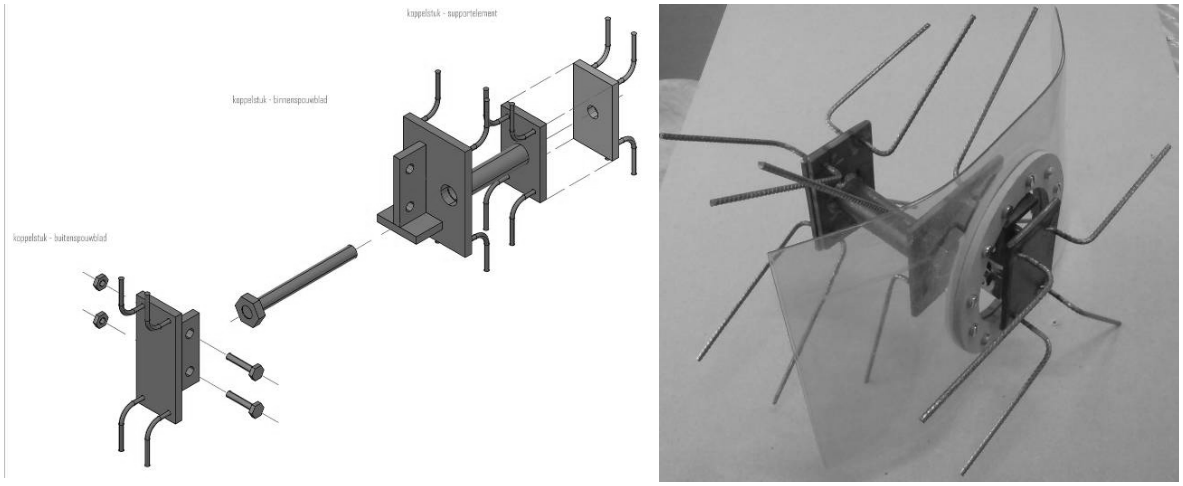

Figure 18: Anchoring the different sections

CONCLUSIONS

The use of flexible moulds to produce free formed concrete elements could play an important role in the development of free form architecture. The use of concrete enables architects to use free formed elements not only as an esthetic feature but gives them also the opportunity to integrate the load bearing function into it. The mock up has shown a bit of the potential that lies in these kinds of structures. By making use of structures deriving from nature it should be possible to work forms that have an innate optimal geometry. Working with tissue structures will enable architects to construct appealing buildings that at the same time will be light in weight and strong as well. For such structures to be build it is vital to have functional and reliable production methods. The process discussed in this paper could pay a role in this stage, but still a lot of work will have to be done. More research could be done on the matter of having control over the deflections of the membranes in relation to the membrane tensions and the occurring hydrostatic pressures in the wet concrete. An important role in the further development of these kinds of structures lies in possibilities of fiber reinforced concrete.

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