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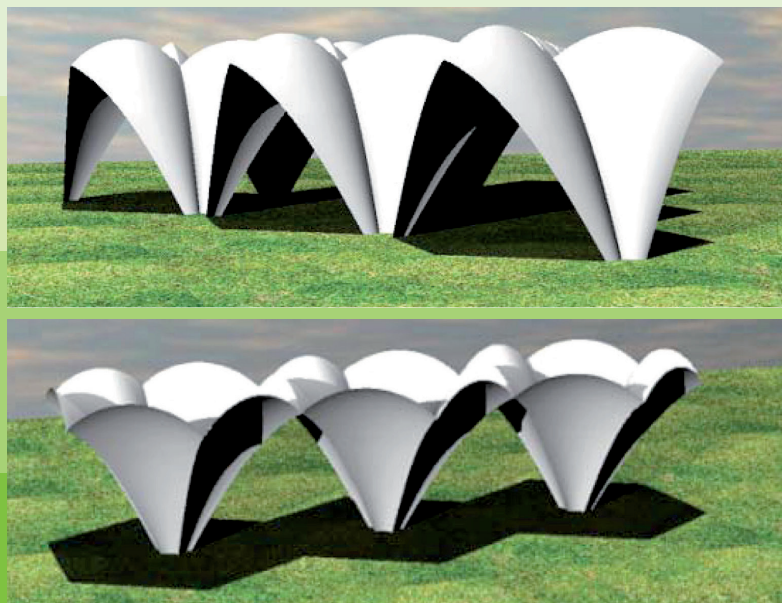


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# STRUCTURAL IMPLEMENTATION OF SLENDER CONCRETE SHELLS WITH PREFABRICATED ELEMENTS

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## ABSTRACT

*Lightweight concrete structures and structurally optimized systems are the focus of several research efforts. This is due to esthetical reasons but also in order to use material in a resource conserving way. Advancements in digitizing planning and fabrication processes, but also ongoing enhancements in material science for cementitious composites enable designers to build complex geometries of slender concrete structures. However, it can be observed that built architecture does not reflect the present possibilities at hand. One reason is the implementation on site; with increasing material performance, the sensitivity of concrete production increases to assure sufficient accuracy, workability and post-treatment. In combination with demands for quick assembly and simple disassembly of structural components, a prefabrication of concrete elements is indispensable.*

*The possibility to reduce cross section dimensions on the one hand and the arising challenge how to realize load bearing connections on the other hand, is a contradiction investigated within this survey. The identification of mechanical principles of structural connections enables the development of design strategies for load bearing connections. Two selected case studies, illustrating adhesive and interlocking bonding of concrete elements are presented, verifying the feasibility on site. An adhesive bonding is presented for a concrete bench, designed as a Möbius strip. This innovative, thin concrete shell structure is built on the campus of the University of Kassel. Due to prefabrication in a concrete laboratory the partition of the object was necessary. An interlocking bonding is applied for the construction of a concrete mobile, designed for an exhibition in Amsterdam. With the focus on a quick and easy assembly and non-destructive disassembly, a micro-prestressing connection method is developed.*

**Keywords:** Slender concrete shells, freeform structures, prefabricated elements, installation on site, (ultra-) high performance concrete, connection methods, morphology, form finding, optimization, digital fabrication

## 1. INTRODUCTION

The current global challenges of climatic and demographic changes are directly affecting the building industry. A significant portion of the required energy during the life cycle of our buildings is covered within grey energy. This is the part of the embodied energy of each building element which is not considered in some of the commissioned certification institutes of sustainable

building design. User demands for the built environment are changing at an increasing speed. This directs to a rethinking of design approaches and building technology.

The construction of thin-walled concrete structures is – beside its aesthetic benefits – one approach to utilize materials in a resource conserving way. Enormous developments over the past decade in digitizing design and fabrication processes enable

the analysis of complex geometries under consideration of multiple boundary conditions. Digital aided manufacturing allows for computer controlled fabrication without an interruption of the digital process chain. [1]

Despite the possibilities of digital tools and production methods, the way of thinking of the construction industry is dominated by the standards of industrial production. Buildings are generally assembled from massive elements under flexural stress (*Mainka et al. [2]*), enabling an unpretentious handling of geometrical data and the construction processes respectively.

Material savings and slenderness are achieved by both the application of high performance materials and the negotiation of the force flow by generating form-relevant structures. The form manipulation towards a load bearing with axial, avoiding in-plane bending stresses, leads to an activation of membrane actions with an optimized utilization of the material, as described by *Eisenbach et al. [3]*.

However, freeform structures having boundary conditions derived from architectural applications may be exposed to in-plane bending, not meeting the membrane stress state. This must be considered within construction concepts.

The production of building elements made of high- and ultra-high performance concrete, embedded within an integral and digital workflow, postulates the prefabrication under laboratory conditions to assure a sufficient accuracy, workability and post-treatment. Minimizing construction times on site, especially in densified urban areas, is a further consideration. Thus, a special focus is put on the construction of joining techniques.

Event architecture, temporary structures and exhibition objects emphasize the demand for efficient assembly concepts: Not only may a quick assembly, but also a simple, sometimes non-destructive, de- and reassembly, be necessary.

The two case studies presented here looked into the depicted subject. They have been realized in an academic context, combining education and research. Following the principle of inventions being emphasized by economical restrictions,

innovative and preferably low-tech connection methods for the realization on site have been developed, fulfilling the requirements of a quick and easy construction on site.

## 2. CONCRETE SHELLS IN ARCHITECTURE

Shells are efficient structures facilitating large spans in relation to the shell thickness. Similar to arches, as mainly used in the design of bridges, the loads are transferred by axial forces. Whereas arches react sensitively to uneven loads due to the one-dimensional arch effect, shells with double curvatures are able to constitute equilibrium without in-plane bending forces, even for uneven loads or shapes, because of the two-dimensional load transfer.

If compressive and tensile forces are oriented orthogonally to the radii of curvature of the shell and shear and bending impacts are negligible, a membrane stress state is obtained. This state, based on effects of absolute strain conditions leads to homogeneous stress utilization over the cross section, in comparison to deformation-intensive bending systems, where central fibers are not contributing to the load transfer.

### 2.1. Systematic classification of shells

There are several definitions and classifications of shells in literature.

One approach is the categorization of axial or rotational symmetry, like ‘cylindrical’ shells, ‘rotational’ and ‘other’ shells. The analytic approach can be divided by the mathematical descriptiveness in ‘algebraic’ and ‘transcendent’ shells. The slenderness, given by the quotient of the shell thickness  $d$  and radius of curvature  $R$  can be a further starting point, categorizing formations to ‘very slender’, ‘slender’, ‘thick’ and ‘very thick’ shell structures. A functional approach distinguishes according to the potential of curvature. ‘One directional curvatures’, as there are cylinders and barrel shells, and ‘double curvatures’ that again can separate to ‘synclastic’ (curvature radii on one side) and ‘anticlastic’ (curvature radii on opposite sides) shapes. A well-known example of the latter is the hyperbolic paraboloid. [4]





**Figure 1:** ILEK, Stuttgart, Germany by Frei Otto – Form active and tensile only structure



**Figure 2:** Service station in Deitingen '68, Switzerland by Heinz Isler – Form passive and compressive only structure



**Figure 3:** Oceanographic Valencia, posthumous construction after the design of F. Candela – Form passive membrane structure with compressive and tensile stresses



**Figure 4:** Crematory in Kakamigahara, Japan '06 by Toyo Ito – Freeform structure bearing compressive, tensile and bending stresses

*Franz Dischinger* (1887–1953), a pioneering German shell designer, acting at the beginning of the 20<sup>th</sup> century, formulated his shell definition in 1928: *Shells are structures, formed with single or double curvature with a thickness that is small in relation to surface extents* [5, own translation]. The Spanish architect *Félix Candela* (1910–1997) who realized numerous concrete shells in Mexico in the middle of the 20<sup>th</sup> century even distinguished between ‘true’ and ‘false’ shells, where true shells are double curved and load bearing under membrane stress state excluding bending impact [6].

The definition of *Dischinger* includes tensile structures like the minimal surface of the *ILEK*, which served as a prototype for the *Expo Pavilion* in Montreal by *Frei Otto* (fig. 1) to the category shell structures. Excluding sole stress modes, however, would consequently exclude pure compressive structures like the service station in Deitingen by *Heinz Isler* (fig. 2), where the form is defined by an inverted hanging fabric. An example of a membrane structure, bearing loads with both compressive and tensile stresses, is the *Oceanographic* in Valencia (fig. 3) that was built according to *Candela*’s design. [4]

A reasonable categorization seems to be the expansion of *Dischinger*’s definition stated above by constraining shells to ‘form-passive’ structures. Contrary to ‘form-active’ systems, the shape of the structure does not adapt in dependency of the outer loading applied [7].

In literature, shell designers do not uncommonly point out that ‘good shells’ should exclude bending impacts. Potentially, it is questionable whether a freeform shell, as shown in the example of the *Crematory* roof in Kakamigahara by *Toyo Ito* (fig. 4) is a good shell or not. The design of the shape is informed by multiple criteria derived from architecture and application in practice. However, the occurrent bending has to be considered by the constructing engineer for the implementation and choice of material. [4]

The conclusion of this section by the authors is the awareness and acceptance of bending action in freeform shells. In any case, a certain bending capacity has to be provided by the design of form-passive structures to counteract imperfections, buckling impacts and concentrated loads. Hybrid

systems, bearing axial forces and bending, can be levelled in a way, so that the material chosen achieves a good distribution of stress utilization. The challenge of the engineering consultant is the exertion of influence from the beginning of the design process, in order to achieve a structure appropriate for the material involved. [4]

## 2.2. Application in practice

In the past decades, much progress has been made to streamline processes of the building industry. Advances in computation, storage, handling and cross-linking of digital information allow automated steps, from planning to fabrication in an undisturbed process chain. *Computer Aided Design* (CAD), as initially applied in manufacturing systems engineering, has almost comprehensively entered the construction sector. Standardized interfaces and interchange formats enable not only the form-finding and capturing of complex geometries, but also the structural analysis and the transmitting of data to *Computer Aided Manufacturing* (CAM). Ongoing research efforts are dealing with enhancements of computational form-finding and optimization methods.

Further and ongoing improvements in the building sector have been made in material science. Focusing on cementitious materials, the strength capacities of concrete are similar to the properties of steel. The development of superplasticizers and the discovery of the positive effect of reactive silica fume lead to the development of high (HPC) and ultra-high performance concrete (UHPC) that has been applicable from the late 1980s. Investigations of reinforcement concepts, like high strength steel fibers and micro meshes, led to composite materials with high tensile and bending tensile strength capacities, ensuring a ductile material behavior of this initially brittle material.

Despite the fact that all prerequisites are met, it can be observed that contemporary concrete shells are rarely implemented on site. The material possibilities and development of complex shapes are not reflected in built architecture. The rebirth of concrete shells is limited to a pavilion-scale and the realization is often reserved to demonstrators developed in academic environments. [4]

One reason for the low establishment of high performance materials is in the first instance a lack

of knowledge. Clients, architects, engineers and construction companies are not willing to take a risk by implementing novel construction techniques and materials. A lack of design rules and guidelines, as well as cost calculations which are not justified appropriately, as well as life cycle costs not being taken into account, are further obstacles. Concrete grades exceeding a cylinder strength capacity of 50N/mm<sup>2</sup> are not yet covered within European standards, thus individual approvals are required for application.

A further rather technical reason can be determined by the feasibility on site. With increasing performance and strength capacities, the precision requirements for the production are increasing. High demands need to be met to achieve a certain fluidity, ensuring the concrete flowing consistently into slender formworks and in between narrow reinforcement gaps. Mixing, casting and curing processes require a certain monitoring to comply with water and air temperatures and post treatment necessities.

As a consequence, building elements made of high and ultra-high performance concrete are restricted to production under laboratory conditions and prefabrication is indispensable. This results the challenge of how to join prefabricated elements on site. The following case studies examine the contradiction of the possibility to reduce cross section dimensions due to advanced materials on the one hand and the complexity of discontinued homogeneity due to prefabrication on the other hand.

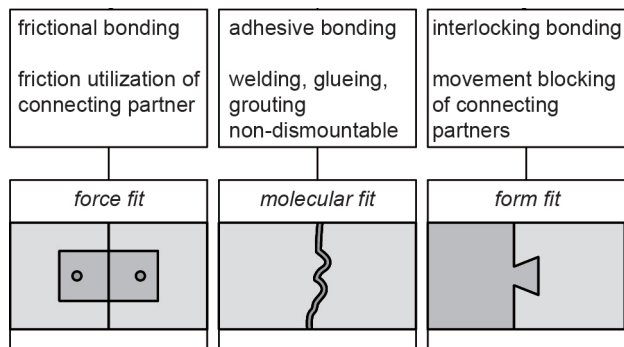
## 3. CONNECTION METHODS

To make the decision for a distinct joining strategy of prefabricated concrete elements, it might be useful to investigate general methods of connections as used in mechanical engineering.

Solid state bodies have six degrees of freedom, three translational and three rotational, describing the mechanical connection to an adjacent element. Connection joints restrict at least one movement of two or more connecting partners. The illustrated pictograms (fig. 5) show the categorization of connection methods according to the action principles in 'frictional bonding', 'adhesive bonding' and 'interlocking bonding'. Connections can be reversible and irreversible, restricting a



nondestructive disassembly. Examples of reversible connections are screwing, clamping and interlocking, whereas welding, gluing or grouting is considered to be irreversible connections.



**Figure 5:** Three available connection principles as termed in mechanical engineering [4]

‘Frictional bonding’ or ‘force-fit’ describes the connection of two adjacent partner elements with a compression force acting on the contact areas. The compression of the elements, which can be obtained by prestressed screws, leads to a frictional bonding. This bonding is kept, as long as the friction is greater than the load transferred by the joint. Usually force fit-connections are reversible, as long as the frictional forces can be released, for example by unscrewing.

‘Adhesive bonding’ or ‘molecular-fit’ describes a connection which is generally not reversible without destruction, since the connection partners are joined via a molecular bonding gained by welding, vulcanization, grouting or gluing.

‘Interlocking bonding’ or ‘form fit’ describes the blocking of a movement in one or more distinct directions of an element given by the connecting partner. Under loading, the contact areas are under compression. Interlocking bonding is generally reversible, as long as geometrical boundary conditions allow for disassembly.

Whereas force fit connections are typically used for steel constructions (screwed connections of steel plates with prestressed screws), the remaining two connection methods ‘molecular-fit’ and ‘form-fit’ form the basis for connections in prefabricated

concrete constructions and are further discussed within this survey.

#### 4. LOAD BEARING ADHESIVE FIT JOINTS

A student project was tendered to design, develop and realize a slender concrete sculpture on the campus of the *University of Kassel*. The time frame for the project was limited to the duration of the summer term. A group of 27 students of the *School of Architecture* worked under the supervision of a mixed team of architects and structural engineers from the *Department of Structural Systems*.

Two boundary conditions have been predefined. Firstly the site: The University has given the construction permission for a prominent spot, visible from all sides, directly in front of the central canteen. Secondly the material: a big pack of high performance concrete, as well as the mesh reinforcement, was sponsored by the industry partner *DUCON®*.



**Figure 6:** Concrete bench ‘Möbiusban(k)d’ after construction on the University campus

The project began with a competition phase, where seven individual groups were asked to find a concept that reacts to the site with a function of their choice. The proposals, covering sculptures, roofs, benches and seats, were reviewed by an external jury which selected one proposal for the following optimization and construction phases.

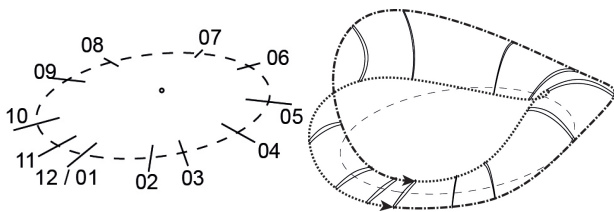
The winning concept was a concrete bench (fig. 6), titled *Möbiusban(k)d* which describes the form of a *Möbius strip*.



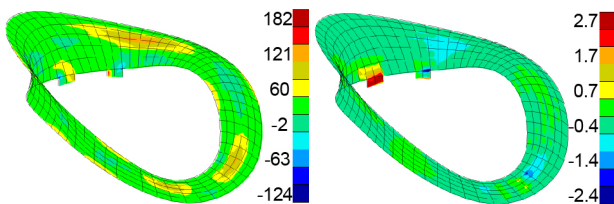
#### 4.1. Conceptual design of Möbiusban(k)d

The envisaged concept of the concrete bench reflects the omnipresence of science at universities. The bench-like sculpture has areas to sit on, to lie on or to lean against. Those areas are defined through the different heights of the bench. The sculpture opens up towards the canteen to invite visitors to take a rest on it.

The geometry is parametric and was built with *Grasshopper*, a plugin for the 3D modeling software *Rhinoceros3D*. First and foremost, the shape of the bench is driven by the design and functional aspects in order to achieve a convenient bench furniture. Having the initial geometry satisfying all functional boundary conditions, the shape has been adapted with an optimization process performed with *Karamba* [10], itself a plugin of *Grasshopper*. *Karamba* allows for a live analysis of the structure, while manipulating the input parameters. With the help of *Galapagos* [11], an evolutionary solver, the geometry can be optimized in predicted frames by the allocation of fitness criteria; in this case, the self-weight deflection [9].



**Figure 7:** Parametric derivation of the shape starting with an initial ellipse, informed by multiple optimization criteria, considering among others, functional, structural, and ergonomic aspects [8]



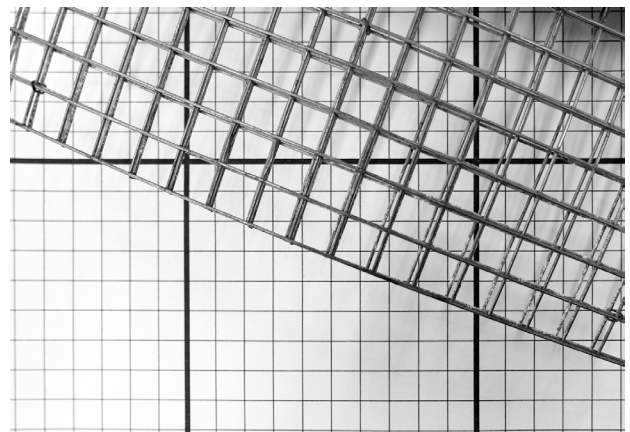
**Figure 8:** Axial force distribution (left) [kN/m] and in-plane bending moments (right) [kNm/m]. The analysis proves the categorization as a hybrid structure

The shell thickness is constantly limited to 22 mm at the edges and widens slightly towards the center of the strip. The total length of the object has been

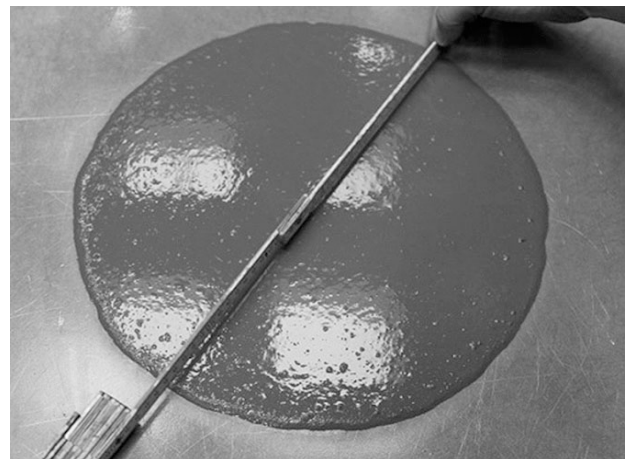
levelled to 3.75 m, the width to 2.45 m and the height to 95 cm.

The structural behavior describes a hybrid load carrying behavior using both axial forces and in-plane bending, not meeting the membrane stress state (fig. 8). The shell is designed via effective stress analysis, legitimated by the used material as described in the following section. The design stress resultant value, considering multiple load case scenarios, is limited to a bending tensile stress of 12 N/mm<sup>2</sup>.

#### 4.2. Micro mesh reinforced concrete



**Figure 9:** Micro mesh wire reinforcement with a bar diameter of 1mm and an axial distance of 12.5mm



**Figure 10:** Slump control to guarantee a sufficient flowability of the concrete for the casting process

Scaling down dimensions of conventional reinforced concrete by a factor of around ten, in order to achieve narrow structural concrete elements, leads to concrete sections with micro reinforcement. Geometrical dimensions like the

element thickness, the concrete cover and the corresponding material components (grains and reinforcement) can be downsized. The dense cement matrix, as achieved by applying a high performance concrete with a cube strength capacity of  $100\text{N/mm}^2$ , allows smaller concrete covers to be used for the sake of corrosion protection. The use of stainless steel in areas close to the surface even allows this protective covering to be omitted. Ready welded micro mesh reinforcement wires provide bi-axial reinforcement with small diameters and small axial bar distances, respectively.

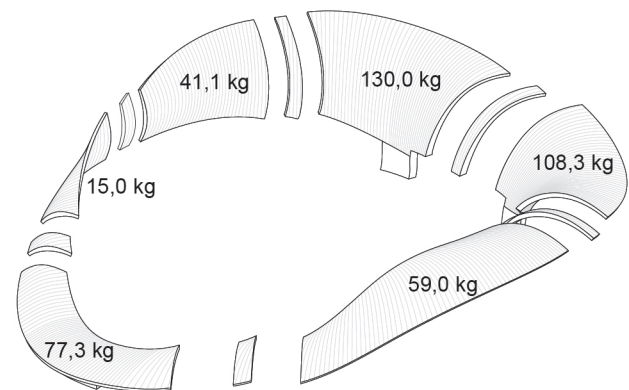
A concrete technology based on the downsized geometry of concrete components is developed by *Stephan Hauser*, founder of *DUCON*, a material supplying company, supporting the case studies presented in this article. *DUCON* stands for 'Ductile Concrete' and represents the combination of high-performance or ultra-high performance concrete with micro reinforcement from steel wire meshes. The mesh wire reinforcement is uniformly stapled over the entire cross section, from the top-to-bottom fiber of the building element to be cast. The chosen mesh wires, six layers in total, have a diameter of  $1.0\text{mm}$  with a mesh grid spacing of  $12.5\text{mm}$ . The resulting homogeneous set up of the composite material has an almost linear gradient of stress distribution by approximation, allowing a linear elastic design procedure via *von-Mises* stress analysis. [4]

There are strict requirements for the consistency of the concrete: To assure the concrete fills the complete formwork, its flowing path has to go through the mesh wires of the stapled steel layers. Therefore the concrete has to be fluid and self-compacting. The maximum grain size of the concrete aggregates has been chosen to  $2.0\text{mm}$  during the design of the grain-size distribution. Prior to pouring concrete, a neat schedule of the mixing process under laboratory conditions has been developed, considering the order of adding concrete components, water temperature, mixing time and machine speed. A minimum slump of  $37.5\text{cm}$  (fig. 10) using a *Hügermann* cone has been investigated to assure a consistent concrete flow. [9]

### 4.3. Joint fabrication strategy

Due to financial and organizational restrictions, the absence of a crane was a design-driving factor from the beginning of the project.

As the material is very sensitive to surrounding environmental conditions during the mixing and casting process, a casting in situ was not possible and the workmanship of the concrete production had to take place exclusively under laboratory conditions.



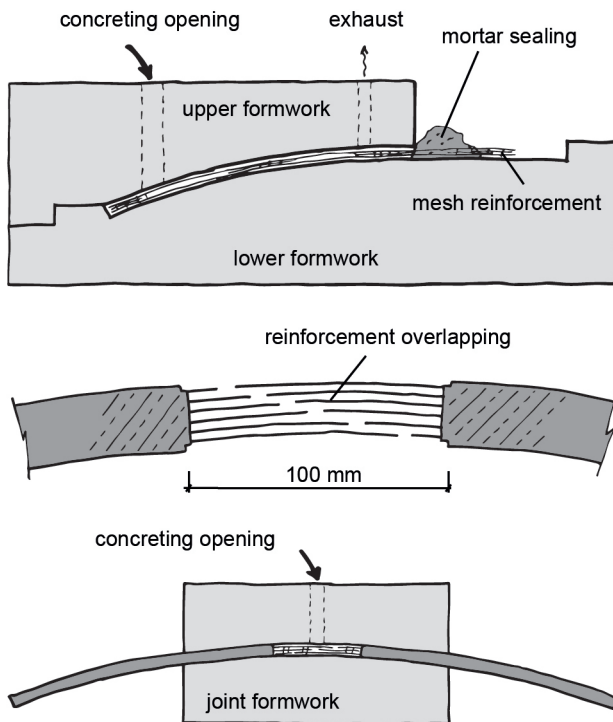
**Figure 11:** Segmentation of concrete bench in order to allow transportation without a crane

Due to the absence of transport devices, a segmentation of the object and hence the development of a segmentation technique has been necessary. A neat planning of the joint locations, the joint widths, and section sizes followed, naturally influencing the design layout.

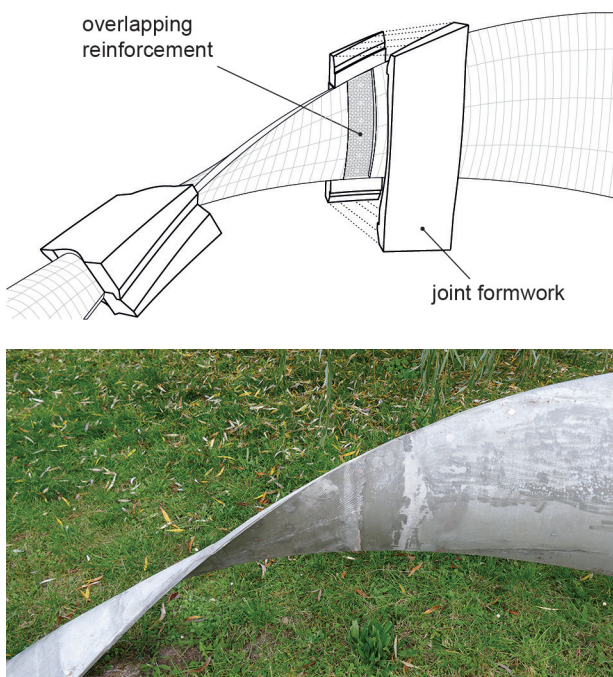
The segmentation layout, as illustrated in fig. 11, is arranged in a way that only a few people are required to carry the single elements by hand and the maximum weight is limited to  $130\text{ kg}$ . [4]

The envisaged construction sequence is intended to be reversed to conventional construction methods: The prefabricated elements are assembled on site and calibrated into position with the help of temporary substructures. After that, the gaps are closed with the casting of individual joint formworks. Finally, the foundations are produced before removing the substructure.

A custom-made segmentation technique is developed, since the project is faced with the demand of fully load bearing joints within the freeform slender shell. This method envisages joints with a width of  $10\text{cm}$  to be cast on site within a second casting step. To ensure the reinforcement is continuously running through the joint, it has to stick out of the formwork of the individual prefabricated elements.



**Figure 12:** Construction sequence for seamless rigid connections is based on the formwork tightening with water soluble mortar



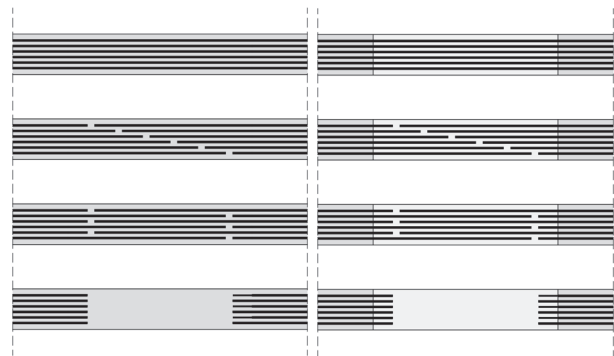
**Figure 13:** Individual pieces were aligned on site and the reinforcement was bent into final position. After that, the formwork of the joint connection is installed, tightened and finally cast. After stripping the formwork a load bearing connection is achieved [4, 9]

The thereby necessary stop ends are realized with water soluble mortar, sealing the formwork within the joint section (fig. 12). The manufacturing of the prefabricated elements of the shell structure in all stages is driven by this segmentation concept. The formworks of the shell elements require a separate mortar bed and each joint has its individual joint formwork installed on site. Fig. 13 illustrates the concept of setting up the formworks of the seams. [4]

#### 4.4. Proof of performance

In order to prove the applied connection method according to the structural performance, several investigations have been undertaken to legitimize a hand-over to the public. Bending tests, proving several reinforcement allocations, are presented here in brevity.

Concrete specimens with a thickness of 22mm and a testing joint-width of 100mm have been produced for four-point bending tests. Fig. 14 illustrates four reinforcement allocations from top to bottom, starting from 'A' (continuous); 'B' (stepped), 'C' (overlapping) and 'D' (disturbed). It may be noticed that the allocation 'A' is not feasible for the joining system, but included in the tests for reference.



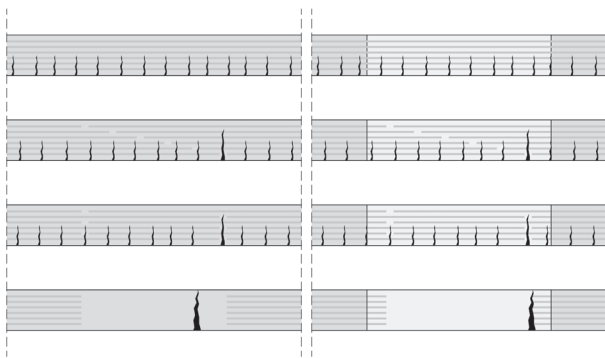
**Figure 14:** Investigated types of specimen cast monolithically 'MO' (left) and in two steps 'FU' (right). Four allocations of reinforcement are set up from top to bottom A-continuous, B-stepped, C-overlapping and D-disturbed

All reinforcement allocations are tested in two variants of production: Cast in one step, thus monolithically as shown left in fig. 14, named 'MO' and according the connection method cast in two steps, named 'FU', as illustrated on the right hand side. All samples have been fabricated several times. The specimens cast in two steps have been



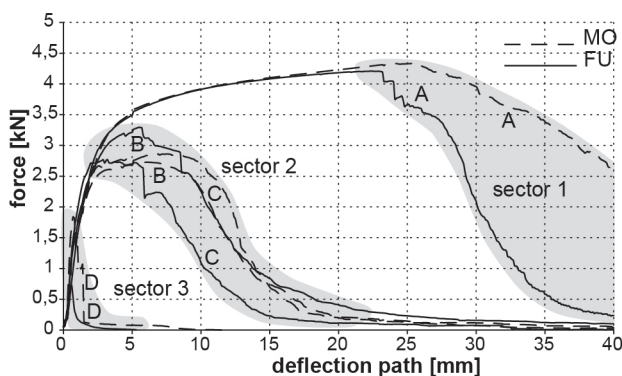
produced with a temporary stop-end made of water soluble mortar to achieve realistic testing conditions.

The qualitative observation of the four-point bending tests undertaken demonstrates a very ductile behavior regardless whether the samples are cast in one or two steps. Large deformations occurred before failure for the reinforcement allocations 'A', 'B' and 'C' and naturally a very brittle failure occurred for the non-reinforced specimen 'D'.



**Figure 15:** Diagrammatic illustration of qualitative crack distribution; from top to bottom the sample types A, B, C and D. The crack formation is not dependent on concreting sequence

As one might suspect, the crack distribution is very consistent for the continuous reinforcement 'A', with many small cracks evenly distributed over the length applied to bending tensile stress. For the allocations 'B' and 'C', an initial cracking occurs at the location of the first discontinuity of the mesh layer closest to the surface under tension. However, the remaining cross section also cracks and the ductile failure behavior is still achieved.



**Figure 16:** Load-displacement plots summarizing the results of all tested concrete samples

Recording the force-deflection paths of the median values of investigated samples results in the graphs illustrated in fig. 16. It may be observed that three major sectors are developing. *Sector 1* incorporates the specimens with continuous reinforcement 'A', naturally showing the best and most ductile failure behavior. *Sector 3* shows the expected poor structural behavior of the samples with no reinforcement within the joint area. *Sector 2* encloses all samples with reinforcement allocation 'B' and 'C', relevant for the connection method developed for the concrete bench. The structural behavior is very reliable until the point of failure and a large post-cracking deformability is achieved, enabling a high ductility. Whether the samples are cast in one or two steps has negligible influence.

The investigation demonstrates the feasibility of the connection method developed. Fully load bearing joints for a hybrid structural shell have been realized. The four point bending tests have shown the insignificant influence of the casting procedure. The influencing effects of the reinforcement allocation are generally occurring regardless of the necessity of joining prefabricated elements, since reinforcement splices have to be implemented.

The authors would like to mention that, although it is not the content of this essay, that the significant potential of this slender concrete shell in regards of sustainability is notwithstanding conflicting with the double-mold for the custom design of the bench.

## 5. DRY FIT INTERLOCKING JOINTS

The organization committee of the 2015 IASS symposium set up an international exhibition contest of structurally innovative pavilions. The competition was tendered to architects, engineers and scientists from all over the world, to realize demonstrators of their research context. The expected standard was described in the tendering document: "...The pavilions have to give a future vision on structural design and innovation and have to be the outcome of excellent structural research."

The exhibition venue was the foyer of the *Muziekgebouw aan't IJ* in Amsterdam, a concert building located in the city center at the south waterfront of the *IJ* and the port entrance of *IJhaven*. With permission from the IASS organization jury to realize the pavilion, the project was set up within the team of the *Department of Structural Systems* at the *University of Kassel*. [4]



### 5.1. *Stable Equilibrium, Installation requirements*

To equalize the contest conditions for all participants, there were restrictions in size and weight for the packaging in order to enable transportation by airplane. The maximum size of a box was limited to  $100 \times 75 \times 65$  cm and the weight to 32 kg per box.

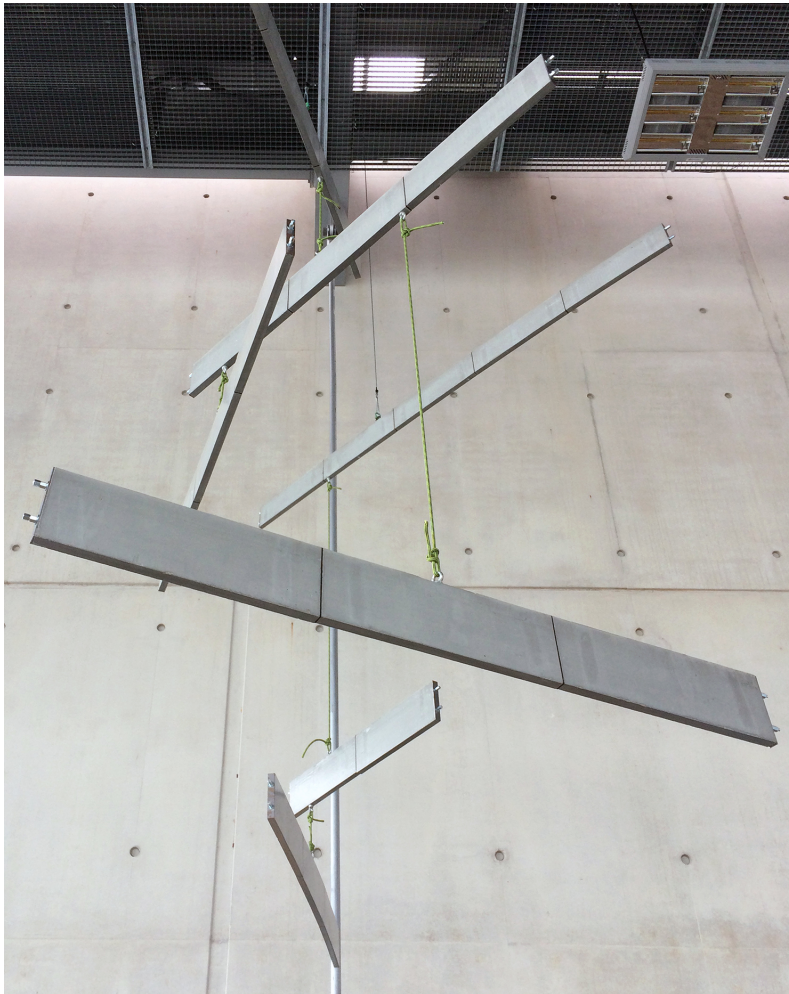
Special demands were made on the construction- and deconstruction times on site. To keep to the daily routine of the concert venue, the construction and deconstruction had to be finished in one day for all participants. This led to a narrow time schedule for the teams and a design-driving boundary condition: Constructions requiring complicated assembly or materials necessitating curing times had to be excluded.

The ambition of the design process was to treat the given rules of the contest as a design criteria rather than a restriction, and incorporate them as

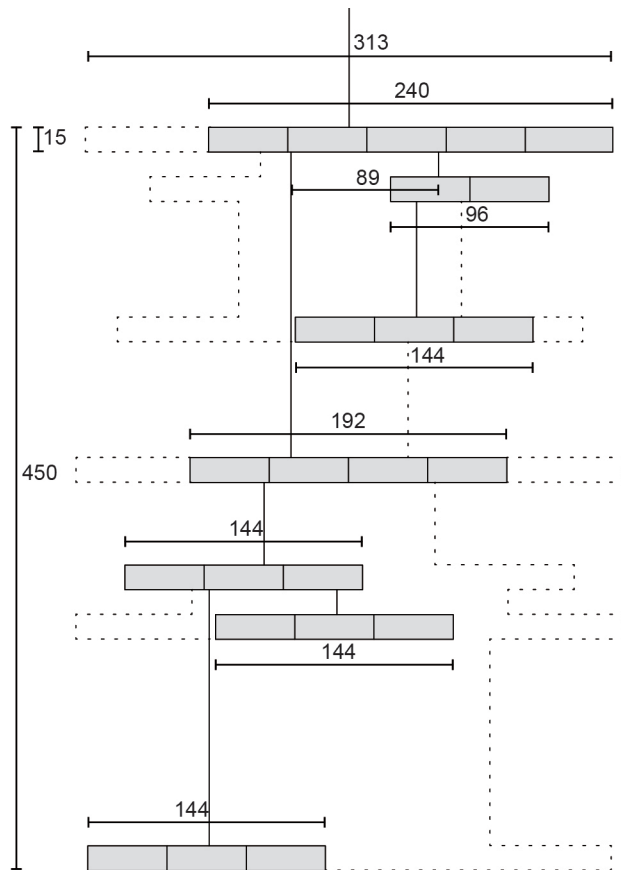
conceptual advantages in the design, instead of splitting a project into pieces based on the packaging size limits [12].

The boundaries derived from the setting of the symposium contest lead to similar demands as above, however, in an exhibition context; prefabrication of the concrete elements is indispensable. A form-fit connection method needs to be applied, enabling not only a quick assembly, but also a de- and reconstruction of the object. The design intent pursued is a suspended concrete structure made of prefabricated concrete elements assembled with a dry-fit connection method.

The structure submitted is a concrete mobile named *Stable Equilibrium* as shown in fig. 18, filling a cylindrical space with  $\varnothing = 313$ cm and a height of  $h = 450$ cm. The structure is assembled of plane elements – thus not a shell. Nevertheless it serves as a demonstrating object of how to join thin concrete elements in a load transferring way.



**Figure 17:** Installed concrete mobile at the exhibition venue Muziekgebouw in Amsterdam



**Figure 18:** System dimensions of the concrete mobile Stable Equilibrium

The structure has a modularization fulfilling the packaging and transportation requirements. All twenty-two elements have the exact same geometry ( $48 \times 15 \times 2.2\text{cm}$ ) with load bearing connections from prestressing devices. The result is a light and floating structure from an initial heavy material that allows a quick and easy assembly on site with an open end spanner as the only tool required. [4]

## 5.2. Bowden cable principal

A *Bowden* cable is a flexible combination of a steel cable together with a hull, initially flexible in transversal direction. The hull has to be compression resistant and functions as a slider for the tendons.

The principle enables a precise decomposition of structural systems into tension and compression; magnitudes and directions of force vectors can be guided to any point of interest. A well-known application is brake cables for bicycles. At both ends of a post-tensioning system the cables release their force as a compression force on the prestressing object. Although the hull is a slender

compression element it does not tend to buckle. As soon as the hull swerves orthogonally to its longitudinal axis, deviation forces arise, acting as a counter force. As long as the material strength capacity of the hulls is not exceeded, the shape of the system is stable and self-calibrating. In the common example of bicycle brakes, an increase of the braking effort and thus, an increase of the prestressing leads to an increase of stiffness, and the cable system turns to be 'harder'. This analogy can be projected to solid elements strung together replacing the compressional hull. A thread running through a number of compressive members leads to a stable system as soon as the thread gets pulled and the system does not tend to buckle, as shown in fig. 19.

The *Bowden* cable principal is a promising conceptual starting point for the connection of prefabricated concrete elements. The high compressive strength as a beneficial characteristic is used to full capacity, whereas the disadvantages, the low tensile strength, buckling sensitivity and small inner lever arm around the weak axis, are retreated [4]. From the stable equilibrium of internal forces

combined with the balancing needs of the global structure of a mobile, the name of the project *Stable Equilibrium* is derived.



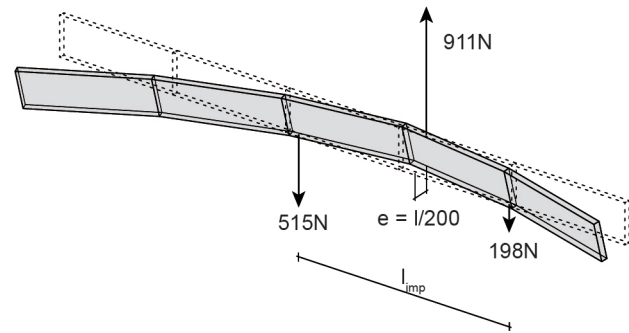
**Figure 19:** Construction principle of a form-fit connection technique demonstrated on a toy giraffe. Internal prestressing is applied with a spring in the base leading to a self-stabilizing structure

### 5.3. Micro prestressing jointing

As described above, the material used is *DUCON*, a reinforced concrete with micro meshes as reinforcement. Simplified, the structural mechanical behavior is analogue to conventional reinforced concrete: A high performance concrete is responsible for the occurring compression, whereas the tension within the section is taken by steel wires that are stapled crosswise over the entire cross section. The placing of the meshes over the complete section guarantees that the tension zones, wherever located, are reinforced. All components of a reinforced concrete section are qualitatively scaled down by a crude factor of around ten, as there are cross section dimensions, diameters and spacing of bars, the concrete cover and grain sizes.

A related concept is disposing a respective scaling for a potential micro prestressing. This method stands for an operation with ‘small’ prestressing media with corresponding narrow axial distances. The tension members, and rather their ducts, must be small enough to fit inside the narrow concrete sections with some space left for some extra reinforcement and concrete cover on both faces. Due to the narrow section and the layers of

reinforcement, the prestressing is located in the center of the cross section [4].



**Figure 20:** Imperfections out of plane require a load bearing capacity in direction around the narrow axis, controlled by gaining the prestressing

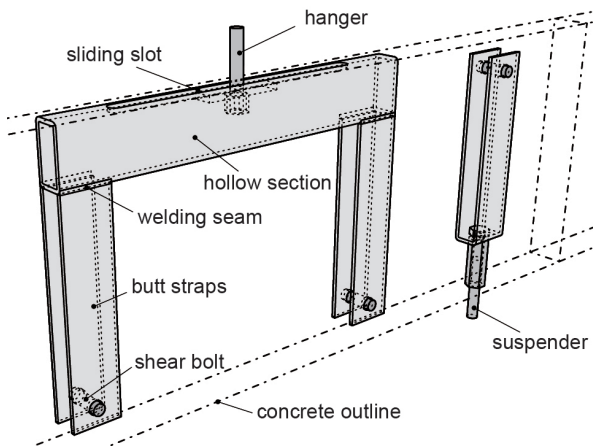
This dry-fit connection method allows the connection of prefabricated elements without embedded items or grouting components, even providing bending stiffness around the narrow axis to counteract occurring imperfections as shown in fig. 20. Threaded rods are used as a prestressing medium. The magnitude of the load applied is controlled by monitoring the number of rotations of the screw nuts.

### 5.4. Installation details

A special aspect of the design of the concrete mobile is the load introduction and the load transfer of the suspensions. Threads, cast inside the concrete sections, provide anchor points where thread eyes are screwed in. Nevertheless, rather high point loads ( $N_{k,max} = 911\text{N}$ ) in relation to the narrow section ( $h = 22\text{mm}$ ) have to be introduced to secure a sufficient resistance against pulling out. These point loads are transferred to the opposite side of the thread. Surrounding the prestressing hulls with cast-in and crotched butt straps, the load is transferred by shear bolts into the concrete section, see fig. 21.

Furthermore, a sliding device was required for each piece of the mobile to allow an exact calibration levelling the mobile during the installation. Located at the top (and thus not visible from below) the sliding of 100mm is enabled by cast-in rails where butt-straps for the load transfer are welded on. Again the space for the centric prestressing hulls is provided.





**Figure 21:** Embedded steel items to transfer concentrated point loads to oppositional side of fittings. At the upper sides, sliding devices are provided to enable calibration

In a nod to a prominent sailing event in Amsterdam at the same time as the exhibition, sailing ropes were chosen as suspension devices and traditional nautical knots were tied in the thread eyes.



**Figure 22:** Dry-fit connection method. The magnitude of the prestressing is controlled by the monitoring of the screw nut rotations



**Figure 23:** Thread eyes are screwed into the anchor points of the sliding device. The suspension items are ropes with running bowline hitches

## 6. CONCLUSIONS

Advancing material properties, especially for cementitious compounds, enable cross section reductions and resource-conserving building constructions. The necessity of prefabrication under laboratory conditions is discussed, revealing the contradiction of the possibility to reduce system dimensions on the one hand, and the need of discontinued element joints, ideally designed to bear unpreventable bending, on the other hand.

Mechanical principles of load bearing connections are identified in order to develop strategies to join prefabricated concrete elements appropriate for the structural system and material involved.

The mechanical principals of *adhesive* and *interlocking bonding* are investigated and tested for load bearing connections of a high performance micro mesh reinforced concrete. The considerations are executed in two architectural case studies, verifying the feasibility of implementation on site.

The survey presents a range of opportunities to realize slender concrete shells and structures with prefabricated elements. The techniques developed are applicable for any geometry at any scale and open up a new variety in the process of slender concrete shell construction for architects and engineers.

## ACKNOWLEDGMENTS

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Participating students for the concrete bench in alphabetical order are: *S. Abbasian, L. Charlet, H. Faizi, J. Fröse, A. Golab, C. Herlitze, D. Koleva, M. Korn, J. Kratzenberg, S. Krieg, N. Kühn, J. Leppin, N. Levsen, A. Lischke, Y. Liu, H. Neusüß, L. Nolte, R. Pfeiffer, T. Reichert, F. Reichmann, J. Rieckmann, A. Rybalchanka, J. Scharf, W. Suchan, A. Steffen, S. Well, C. Ward*. Participating student for the concrete mobile: *M. Hellmann*.

## PHOTO CREDITS

Figure 3: *Oceanographic Valencia*, Photo: *CMD Ingenieros*

Figure 4: *Crematorium* in Kakamigahara, Photo: *Toyo Ito & Associates, Architects*

Figures 1-2, 5–9, 10–23: From [4], © *P. Eisenbach*

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