Seamless rigid connections of thin concrete shells – a novel stop-end construction technique for prefab elements

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Seamless rigid connections of thin concrete shells – a novel stop-end construction technique for prefab elements

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Abstract

Lightweight concrete structures and structurally optimized systems are in focus of several research interests – not only due to architectural motivations but also in order to use material in a resource conserving manner. One significant challenge within the fabrication of slender shells often occurs with the construction of load bearing joints.

On the campus of University Kassel one can find an innovative, form active, ultrathin concrete shell structure designed as a Möbius strip. Due to the prefabrication in a laboratory as well as the absence of a crane it was mandatory to partition the object and to assemble elements on site.

The chosen material is DUCON®, which stands for DUctile CONcrete. It is a composite material of a high-performance concrete and a micro reinforcement of multiple layers of interconnected steel wire meshes stapled over the entire cross section.

The structural concept envisaged a fully rigid system so a novel stop-end construction technique for the mesh reinforcement was developed. To guarantee the rigidity of the connected joints, the reinforcement layers need to overlap and thus the requirement of casting stop-ends for the mesh reinforcement occurs. The solution is the preparation of the joint with a water soluble mortar, placed at the connection boundaries of the prefab shell element that can be washed off after the curing process of the concrete. The joint itself is then cast individually on site.

An extensive investigation of the load bearing capacity of the join system has been executed with four-point bending tests. The appraisal of the force-deflection diagrams as well as the fracture appearances and distribution of cracks validates the developed connection system as feasible.

Keywords: Slender concrete shells, stop end techniques, water soluble mortar, reinforcement arrangement, mesh reinforcement, ductile concrete, load-bearing capacity, rigid shell joints.

1. *Structural Surface* – processing of a slender concrete object

1.1. Campus competition

In April 2014 a student project was tendered to design, to develop and to realize a slender concrete shell on the campus of the University in Kassel. The time frame for the project was limited to 14 weeks - the duration of the summer term. A group of 27 students of the school of architecture in their bachelor- and master studies 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 on 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 has been sponsored by the industry partner DUCON®.

The project started up 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, have been reviewed by a mixed jury who selected one proposal for the following optimization and construction phases.

The winning concept was a concrete bench, which describes the form of a Möbius strip.

Figure 1: Concrete bench after construction.

1.2. Concept of winning design

1.2.1. The Möbius strip

The Möbius strip was discovered by the mathematician August Ferdinand Möbius in 1858 and describes a surface with only one edge. Taking a strip of paper, twisting one end 180° and sticking the ends together gives a Möbius strip. Even cutting the entire strip at the half doesn´t lead to two strips –

it remains one. Möbius strips don't have in- and outsides. If one starts to paint one apparent side, the whole strip will be colored at the end.

1.2.2. Architectural function of concrete bench

The envisaged concept of the concrete bench reflects the omnipresence of science at a university. 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.

1.3. Structural system

1.3.1. Shape optimization

The geometry is parametric built with *Grasshopper*, a plugin for the 3d modelling 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*, Preisinger [1] itself a plugin of *Grasshopper*. *Karamba* allows a live-analysis of the structure while manipulating the input parameters. With the help of *Galapagos*, Rutten [2], an evolutionary solver, the geometry can be optimized in predicted frames by the allocation of fitness criteria, in this case, the self-weight deflection. An in depth description of this process can be found in Rumpf *et al.* [4].

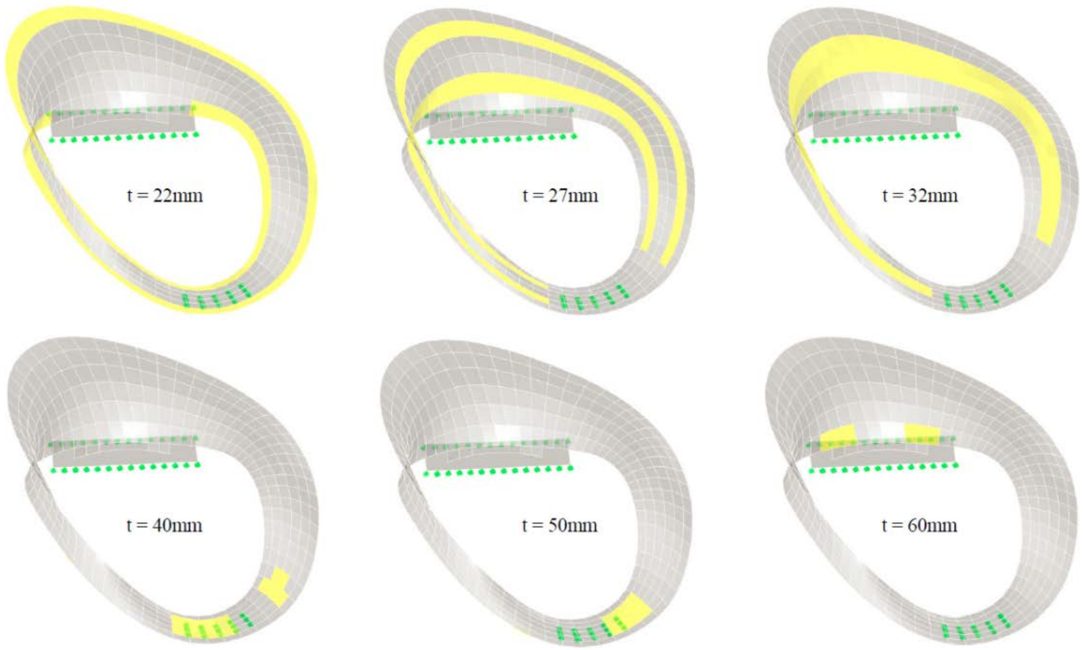

Figure 2: Concrete shell thicknesses.

The final shape and the shell thicknesses of the concrete for the preparation of the milled foam formwork are shown in figure 2.

The total length of the object has been levelled to 3,75m; the width to 2,45m and the height to 95cm.

1.3.2. Loading and load combinations

For the design of the shell the self-weight (computer generated) and the live loads are taken into account. The live load has a magnitude of 2,5kN/m² on the projected surface area. The live load is separated in three load cases; left-only, right-only and fully loaded. The fully loaded load case is governing for the design of the concrete shell; the one side loaded load cases are governing for the foundation and the flipping over resistance.

All load cases are combined with the safety factors of $\gamma_G = 1.35$ and $\gamma_Q = 1.5$.

1.3.3. Material

The chosen material is DUCON®, which stands for DUcile CONcrete. It is a composite material that combines a high performance concrete with a compressive cube strength capacity of 100N/mm² and micro mesh reinforcement from steel wires. The DUCON® technology has been developed by Dr. Stephan Hauser. The crosswise allocated reinforcement bars have diameters of 1mm and the axial distance between the bars is 12,5mm. Those meshes are stapled layer wise over the entire cross section and interconnected to a 3D-mesh-system so that the reinforcement is uniformly distributed. The high ductility achieved hereby allows an approximate linear elastic structural design via principle stress analysis. Eisenbach *et al.* [3].

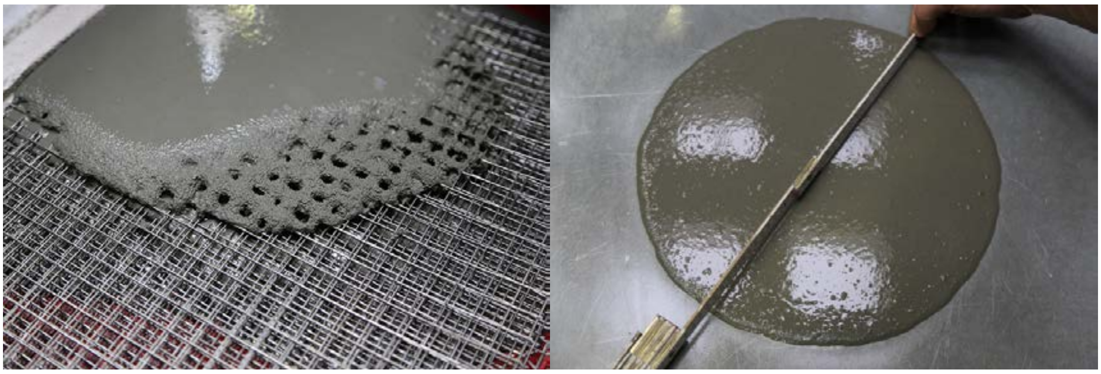

Figure 3, 4: The mesh wire reinforcement is a multiple layer system over the entire cross section of the shell. That leads to high requirements to the fluidity and hence the mixing process of the concrete controlled with the slump before pouring into the formwork.

The steel layout within the cross section is without any concrete cover; therefore the outer three layers are stainless less, whereas the inner layers are carbon steel wires. There are high requirements to the consistence of the concrete: To assure the concrete filling 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 max. 2,0mm when the grain-size distribution curve has been designed. Prior pouring concrete a neat time lapse of mixing process under laboratory conditions has been developed taking into account the order of adding concrete components, water temperature, mixing time and machine speed. A minimum slump of 37,5cm using a *Hägermann* cone has been investigated to assure a consistent concrete flow.

1.3.4. Assessment of state of strain

A structural design considering effects of second order theory has been investigated to predict the shell thicknesses and global stability. Main focus of the analysis is the differentiation between a load transfer via in-plane bending stresses versus membrane stresses (axial tensile and compressive loads). In areas with in plane bending forces the shell thickness had to be amended in order to achieve the sufficient statically height. The final design was then controlled via the principal stress utilization. The design stress resultant value under worst load case scenario is reduced to ~12N/mm².

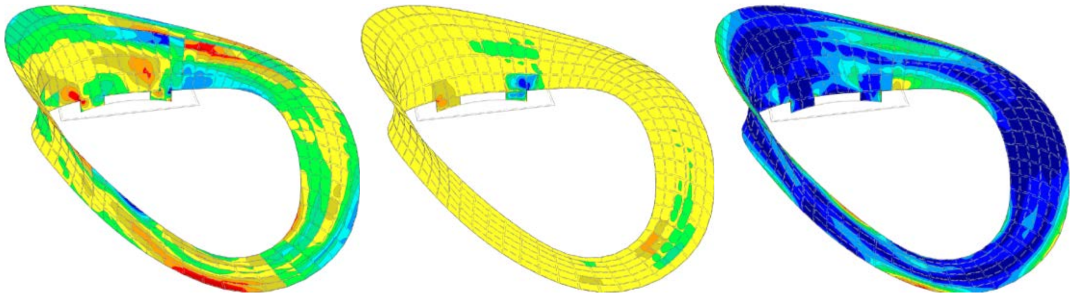

Figure 5, 6, 7: From left to right: Axial stress distribution diagram (red:=tension, blue:=compression); in-plate bending moments (yellow:~zero); principal stress distribution.

1.3.5. Buckling analysis

Due to the slenderness of the concrete shell a buckling investigation is mandatory since it might be the governing failure design criteria. The areas of interest are those with compressive membrane forces at the outer edges where the shell has the smallest thickness and the smallest curvature. With a nonlinear analysis the governing buckling shapes investigated. An imperfection of the shape imposed dependent on the length of the compressed edge. The buckling capacity is controlled by checking principle stresses under the influence of 2nd order analysis before and after the modelling of the imperfections.

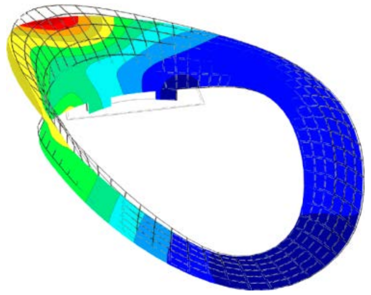

Figure 8: First failure eigenmode from buckling analysis.

1.3.6. Foundation

The design of the footing is driven by the requirement to achieve a resistance against flipping over in case of the object being loaded on one side only. This is guaranteed with a mass foundation wide enough to have a lever arm below ground to stabilize the shell.

2. Construction progress strategy

From the beginning of the project the absence of a crane was a given boundary condition for the design of the bench. Additionally the concrete could not be poured on site – this had to be done under laboratory conditions. Therefore the need of a segmentation and hence a connection technique to bring the single pieces together on site had to be developed. It was decided that the individual parts are restricted in weight in way that three people are able to carry it from the concrete laboratory to the site. Therefore the self-weight was limited to 70kg. Furthermore as the construction sequence it was intended to bring the parts in position and to align them according final layout. As the second step the formwork of the joints was installed on site and the connection was casted to achieve a load bearing transition. The last step of the construction then is the casting of the two foundations before removing the scaffolding.

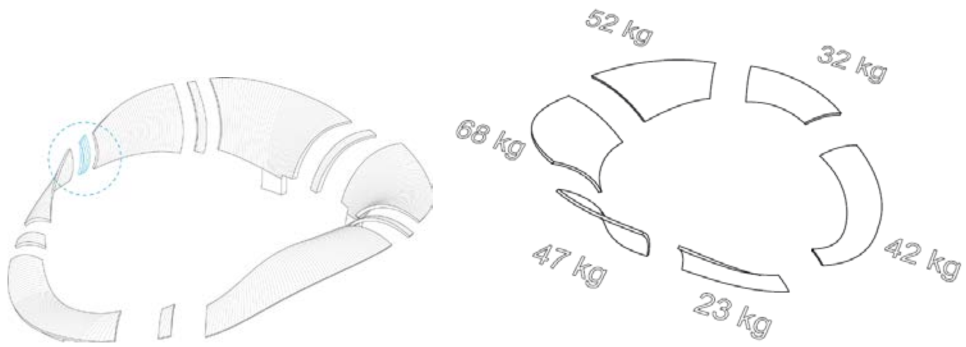

Figure 9, 10: The location of the joints is determined geometrically to fit within in layout and the self-weight was limited to 70kg to be able to carry by hand.

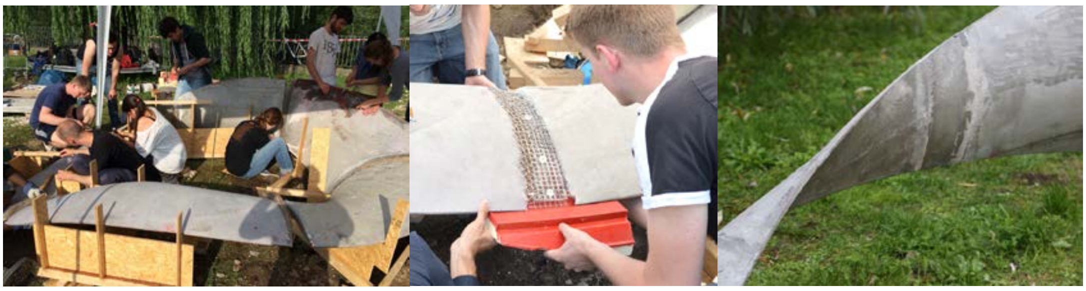

Figure 11, 12, 13: From left to right: The individual pieces were aligned on site and the reinforcement was bent in final position. After that the formwork of the joint connection is installed and tightened and finally cast. After stripping the formwork a load bearing connection is achieved.

3. Segmentation technique

3.1. Stop end techniques

Wherever concrete elements are separated with a continuous reinforcement running through a stop end system is applied. Typical examples are contractions- or settlement joints in foundation mats of buildings where movement restraints from the construction period are temporized. Those joints are closed when the movement already occurred. But the challenge how to apply the formwork in areas of existent reinforcement appears whenever concrete elements are cast in several time steps. This can be done simply by using wooden formwork elements where the breakthrough of the reinforcement bars is drilled in. Since this option is quite labor intense, not only for the assembly but also for the stripping of the formwork, a common option is the usage of expanded metal pieces where the reinforcement is punched through. These metal meshes are at the end lost in the formwork and are bringing the benefit of the achievement of a rough contact area to transfer the shear forces in the joint.

This technique is not applicable since mesh wire reinforcement is used for this project. Dr. Stephan Hauser from DUCON has developed a procedure for the casting of industry floors reinforced with 3D mesh wires: The joint lines can be positioned with a small embankment of sand. With the usage of self-compacting concrete the sand is not pushed away. After the concrete is cured the sand can be simply removed with a vacuum device.

3.2. Sealing of formworks with water soluble mortar

Neither the application of expanded metal sheets is possible in this project, nor the technique of the sand ridge because of the hydrostatic concrete pressure. The most extreme shell element reached a pressure height of ~70cm which lead to a hydrostatic pressure of ~18kN/m². The formwork has to be absolutely tight. Otherwise the concrete would pour out of its formwork. The water tightness is also required at those parts where the connecting reinforcement is sticking out (generally two sides).

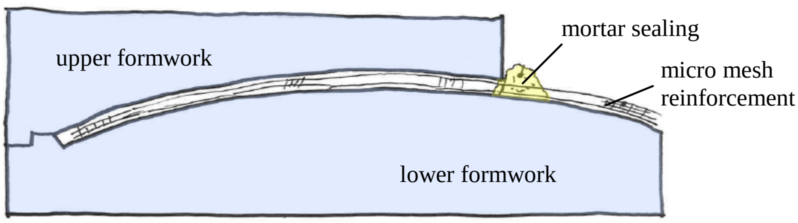

Figure 14: The concept of tightening the milled formwork envisages the usage of a water solulable water that can be washed of after hardening of the concrete element

The sealing in areas of reinforcement has to be stable enough to resist the concrete pressure; on the other hand it needs to be simply removed without damaging the reinforcement mechanically. The solution developed for this building task is the usage of a water soluble mortar. The binder of that mortar is lime. The common application is plastering of interior walls. After hardening the mortar can be removed by washing it out with a strong water hose. With that system the reinforcement does not get affected.

4. Experimental joint testing

4.1. Micro mesh reinforcement arrangement

The structural concept envisages a fully rigid joint with full bending capacity even in the crossover sections of the connection between two concrete shell elements. Using the stop end technique with the water soluble mortar certainly leaves lime remains even after washing off the temporary sealing. To find out whether to concrete texture is disturbed, and if so, if this has an influence in the capacity of the section four-point bending tests are carried out.

To achieve most accurate results in terms of the tensile bending capacity the samples produced are flat without any curvature.

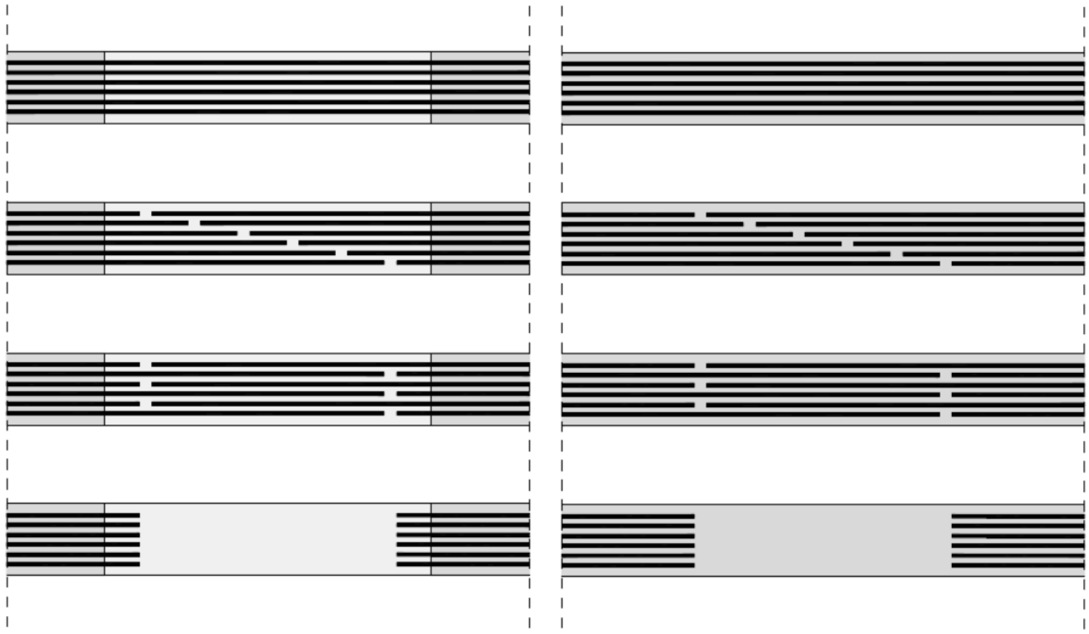

Figure 15: Four different reinforcement arragements are considered within the investigation: From top to bottom the samples Type *A*, *B*, *C*, *D*; left the casting in two stages "*FU*"; right the monolithically casting "*MO*".

The samples have a thickness of 22mm, which is the smallest size used for the concrete object illustrated above. Furthermore the width of the joints of 100mm is adopted from the design of the Möbius bench. The reinforcement layout is arranged for six layers of micro mesh reinforcement which has the following geometrical data:

Rebar diameter: Ø = 1mm

Rebar distance: e = 12,5 (80 wires / meter)

Rebar layers: n = 6

$A_s = \pi \cdot (1mm)^2/4 \cdot 80 \cdot 6 = 377,0\ mm^2/m$

$A_c = 1000mm \cdot 22mm = 22.000\ mm^2/m$

Reinforcement ratio: 1, 71 Vol.-% per direction.

There are four reinforcement layouts investigated as illustrated in figure 15: Type *A* – continuously in the section; Type *B* – overlapping with thrusts distributed equally over the width of the joint; Type *C* – overlapping with two locations of the thrusts within the joint; Type *D* – no reinforcement within the joint. These four reinforcement layouts are respectively tested in two different casting situations: Type *FU* – the flanges are cast first with the water soluble mortar joint. The joint itself is cast one day later after washing off the mortar; Type *MO* – the samples are cast monolithically in one piece. For each version three samples are tested. This leads to 4 (*A*, *B*, *C*, *D*) x 2 (*FU*, *MO*) x 3 = 24 samples.

4.2. Experiment set-up

The four point bending test is carried out for each of the 24 samples. The samples have an overall length of 500mm, a width of 150mm and a thickness of 22mm. The spanning length of the supports of the machine is positioned to 400mm. The test force is separated with a rocker in *2· F/2*. The distance of these impact bars is 20mm to secure the position to be outside the investigated joints. With this set-up a constant bending moment over the entire width of the joints is guaranteed.

There are two different ways how to apply the testing load; *driven over the force*, where the force is increased within predetermined time steps and the corresponding displacement is recorded; and *driven over the way*, where a way in force-direction is applied within predetermined time steps and the corresponding force is recorded. In this case the tests are driven over the way to achieve the magnitudes of the remaining load bearing capacity after failure.

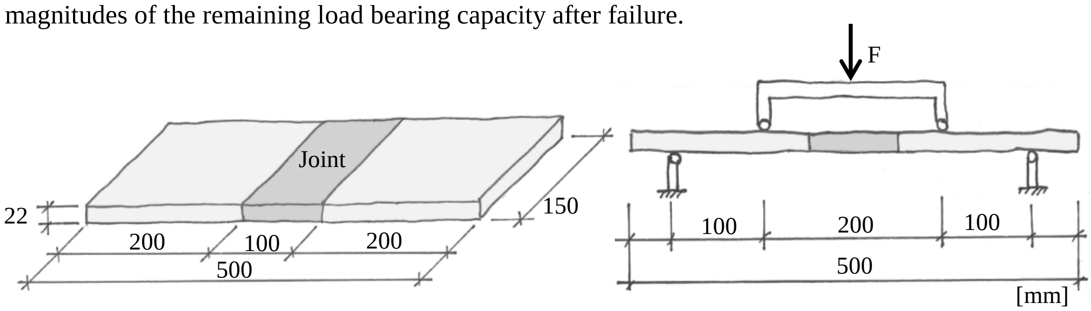

Figure 16, 17: Twenty-four concrete samples are investigated with the four point bending test set-up. The four point bending approach guarantees a constant bending moment distribution over the width of the joint.

The samples where all build and reinforced with open formworks from medium density fiberboards (MDF) where the surfaces are laminated with synthetic foils at the concrete contact areas. The samples cast in two stages are getting the mortar sealing in the joint area first before the flanges are cast. The casting of the joints is done twenty-four hours later after the mortar is washed out. The whole test time frame is organized in a way that the testing with the four point bending machine is exactly 28 days after casting of the joints and hence the whole sample for the monolithically cast versions.

Figure 18, 19, 20: From left to right: Mirco mesh reinforcement in the joint area. This example shows the overlapping version, type *B-FU*; the mortar sealing is washed out before casting the joint; four point bending test setup. The sample illustrates the ductile behaviour of the micro mesh reinforced concrete.

4.3. Results

4.3.1. Crack behavior

As a result naturally the magnitudes of the failure load are of mayor interest. Never the less the qualitative crack behavior is not less important. The ductile behavior is one advantage of the micro mesh reinforced concrete, because of its high load bearing capacity after failure. The wanted crack layout over the building element is well distributed with small cracks and a small crack distance. This crack formation is given where the reinforcement is continuously placed over the length of the building element. As soon as there is a thrust within an area of high bending moment initial cracks may occur at those areas as shown in figure 21. The investigation shows that those starting cracks are always in areas where the reinforcement is disturbed – not in those areas where the casting separation is located.

4.3.2. Load bearing capacity

The test equipment machine records the force- and displacement data over the entire testing period. Since the tests are controlled over the displacement way the maximum peak load is equivalent to the failure load. From this maximum force the maximum bending moment can be derived as max M = $F/2 \cdot 100mm$ [Nmm]. With the section modulus $W = b \cdot h^2 / 6$ [mm³] the maximum bending tensile stress capacity can be derived with $\sigma = M / W$ [N/mm²]. These magnitudes are illustrated below as arithmetic mean values from minimum three samples in each case.

Note: During the test also the remaining load bearing capacity after the point failure is recorded and interpreted. For the ultimate load design of the concrete Möbius shell the breaking loads are considered only, therefore the force-deflection diagrams are not shown in this paper.

Samples cast in two stages with the joint “FU”:

Type *A*: σ = 14, 8 N/mm²

Type *B*: σ = 11, 1 N/mm²

Type *C*: σ = 9, 6 N/mm²

Type *D*: σ = 2, 8 N/mm²

Samples cast monolithically “MO”:

Type *A*: σ = 16, 8 N/mm²

Type *B*: σ = 10, 1 N/mm²

Type *C*: σ = 10, 7 N/mm²

Type *D*: σ = 8, 4 N/mm²

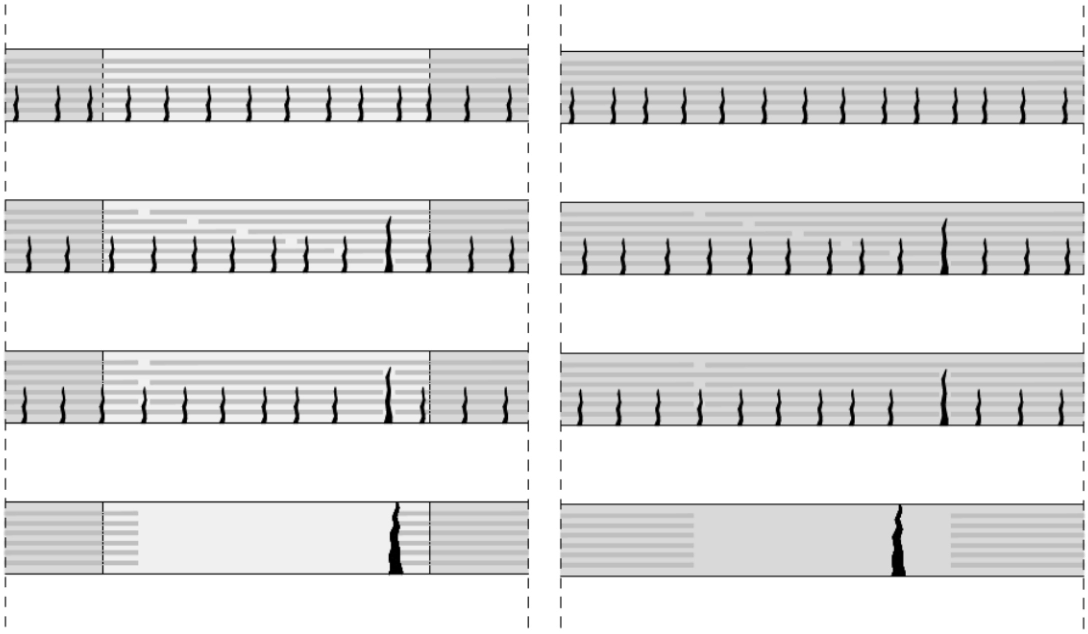

Figure 21: These sketches are showing qualitatively the crack distribution of the samples cast in two stages (left) and the samples cast monolythic (right). The location of the initial crack is dependant on the reinforcement distribution within the section.

It can be noticed from the results that the main influence in the load bearing capacity is coming from the reinforcement layout and not from the fact if the sample is cast in one or two pieces. Especially the samples of main interest *B* and *C* (used in the Möbius-bench) are showing that there is almost no influence of the disruption of the concrete texture. Whereas in samples *D*, where no reinforcement is used, the tensile strength capacity of the concrete is decisive and hence the samples cast with the joint have much less capacity. The failure crack in this case is located directly at the crossover.

5. Conclusion

There are many ongoing research efforts to minimize the thicknesses of building elements made of concrete. Many interests are focusing in the increase of the composite material components like ultra-high performance concrete (UHPC). This may result in the fact that those composite sections can be produced under laboratory conditions only, which leads to the question how to assemble single items on site.

With this research project, which arose during the design process, the authors were faced with the question how to bring single pieces together without losing load bearing capacity. The finding of a new stop-end technique for double curved concrete sections armed with micro mesh reinforcement is applicable for any geometry at any scale and opens up a wide variety in the planning process of slender concrete shells for engineers and architects.

Acknowledgement

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