Experimental investigations on actively bent concrete shells

Johannes Berger1 | Oliver Gericke2 | Jürgen Feix1 | Werner Sobek2

1Unit of Concrete Structures and Bridge Design, University of Innsbruck, Innsbruck, Austria
2Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart, Stuttgart, Germany

Correspondence
Johannes Berger, Unit of Concrete Structures and Bridge Design, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck, Austria.
Email: johannes.berger@uibk.ac.at

Funding information
Österreichische Forschungsförderungsgesellschaft, Grant/Award Number: COMET-860474-TCCV

Abstract
This paper concerns a novel method of constructing shell structures from flat concrete plates by means of active bending. The method is described together with a series of experimental investigations. The theoretical background for this method is given in Berger et al., Actively bent concrete shells, Struct Concrete, 2020. The method makes use of the high capacity for rotation exhibited by thin concrete plates that are reinforced with highly elastic tensile reinforcement. When these plates are subjected to eccentric forces introduced by external tendons they are raised and bent precisely into a desired curved shape. The method was investigated and refined along with a series of experiments which are the subject of this paper: uniaxial tensile tests on rovings to determine their elongation at fracture, bending tests on small concrete plates to determine possible radii of curvature, and large-scale tests to demonstrate the erection process of actively bent shells.

KEYWORDS
active bending, experiments, membrane, shell, tendon, textile-reinforced concrete

1 | INTRODUCTION

Shell structures, both structurally and architecturally sophisticated, have been used for centuries1–3 for simple utility structures or for buildings with a high representative character. Nowadays, however, their implementation is often difficult due to the high costs of their construction. In recent decades, several construction methods have been developed with the focus to make shells more economic: for example, the production of tailored formwork4–6 or pneumatic constructions.7,8 Bending can, therefore, be used to create complex spatially curved structural systems from initially linear or planar structural elements. This design approach enables the development of highly efficient structural systems that result from the short-circuiting of restoring forces.9,10 These so-called bending-active structures are curved structures whose geometry and stiffness result from elastic deformation of their structural elements. Using bending as a self-forming process in construction is relatively unknown.

At the University of Innsbruck, a method for the production of shells was developed that is based on actively bending hardened concrete slabs into a curved shape by applying eccentrically forces.11 These forces are generated by tendons that are coupled to the statically determined slab and subsequently tensioned. The slab’s cross section is required to exhibit a high capacity of elastic rotation by means of a low thickness and a high elasticity of the reinforcement. Upon the erection of the shell, additional measures are required to enable a rigid final structure.
that exhibits a proper load-bearing capacity. These systems can turn into structures or formworks for structures by the means of stiffening or bracing in order to take asymmetrical live loads. The experimental studies conducted to verify this approach are presented in this paper.

2 | UNIAXIAL TENSILE TESTS

The success of the bending process of a textile-reinforced concrete plate to a shell largely depends on the elasticity of the tensile reinforcement. In textile concrete structures, rovings-resin-impregnated multifilaments are commonly used as reinforcement elements. Some fiber materials commonly used in concrete structures together with their mechanical properties are given in Table 1. It shows that textile reinforcement can achieve elongations at failure of more than 40‰.

Textile reinforcement products with building approval are scarce. Therefore, the reinforcement was investigated in a series of tests. The technical data of Alkali Resistant (AR)-glass and carbon fiber (CF)
reinforcement, offered as grid reinforcement, was provided by the manufacturer. Therefore, only the aramid and basalt rovings were tested. Uniaxial tensile tests were carried out on resin-impregnated rovings, is shown in Figure 1. Table 2 lists the determined mechanical properties of the fiber materials. The highest failure strain was achieved with aramid fibers (AFs) with \( \varepsilon_{fu} = 2.7 \% \).

### BENDING TESTS ON SMALL SPECIMENS

The failure strain of textile reinforcement is usually smaller when specimens are subjected to bending compared to a pure tensile loading. Therefore, additional bending tests were performed to determine plausible values as the basis for planning large-scale tests. The influence of different concrete strengths on the curvature potential was investigated.

A set of specimens was produced that measured L/w/h = 100/15/3.5 cm, is shown in Figure 2. Concrete with strengths of \( f_{cm,cyl} = 100 \) MPa (C100) and \( f_{cm,cyl} = 40 \) MPa (C40) and tensile reinforcement made from CF, glass fiber (GF), and AF were used. The reinforcement was placed in the center with a concrete cover of 8 mm on either side.

The fracture test was carried out in the form of a four-point bending test (Figure 3). The two load introduction points are positioned at a distance of 40% of the span to their closest support, thus ensuring pure bending action between them. From the measured deformation, the radius of curvature \( R \), and subsequently the elongation at failure of the tensile reinforcement \( \varepsilon_{tu} \), could be deducted. Similar experiments were carried out by Kromoser.15

The failure strain of the textile reinforcement in the bending tests (Table 3) is smaller than that seen in the tensile tests (Table 2). Also for a specimen with glass or CF, the concrete C40 caused a significant increase of the failure strain over the concrete C100. The highest failure strain of \( \varepsilon_{tu} = 20\% \) was measured at the AR-glass reinforcement with the concrete C40. The tests yielded valuable information for the configuration of the large-scale experiments.

### Table 3

| Specimen | R (cm) | \( \varepsilon_{tu} \) (%o) |
|----------|--------|-----------------|
| CF-C100  | 211    | 8.8             |
| CF-C40   | 165    | 12.2            |
| GF-C100  | 132    | 15.9            |
| GF-C40   | 113    | 20.0            |
| AF-C100  | 124    | 16.5            |
| AF-C40   | 123    | 16.5            |

### Table 4

| Quantity                        | Symbol | Magnitude | Unit   |
|---------------------------------|--------|-----------|--------|
| Mass                            | m      | 612       | g/m²   |
| Young’s modulus                 | \( E_t \) | 72,000    | MPa    |
| Tensile strength                | \( f_t \) | 1,700     | MPa    |
| Fiber cross-sectional area      | \( A_t \) | 87        | mm²/m  |

**FIGURE 3** Experimental setup—bending test

**TABLE 3** Results of bending tests

**TABLE 4** Mechanical properties of the AR-glass reinforcement used in bending test #1

**FIGURE 4** System of the experimental setup
BENDING TESTS ON LARGE TEST SPECIMENS

4.1 Large-scale bending test #1

The first large-scale test was carried out to prove the feasibility of the approach of actively bent shells. The specimens consisted of a textile-reinforced concrete plate (L/w/h = 300 cm/50 cm/4 cm) that was made from a high-strength concrete ($f_{cm,cyl} = 100$ Mpa) with a maximum grain size of 3 mm and an AR-glass reinforcement grid\textsuperscript{16} (Table 4).

The bending was induced by means of steel components for the load application and deviation saddles for a tendon, which were screwed to the concrete plate (Figures 4 and 5). A rubber plate with a thickness of 5 mm was inserted in between concrete and steel components.

A monostrand-tendon with a cross-sectional area of $A_p = 150$ mm$^2$, material grade St1570 / 1,770, and Polyethylene jacket was used. The tensioning force was applied by a prestressing jack, which was controlled by a hydraulic hand pump allowing for precise control.

The tensioning force was applied stepwise throughout the test. In the early stages, a regular crack pattern occurred, is shown in Figure 6, and the curvature of the plate increased proportionally to the applied force. To document the performance the deformation at defined points was measured and the radius of curvature was deducted. At a minimal radius of 3.25 m a shear crack opened at the end anchor, see Figure 7. The experiment had to be stopped before the GFs failed. However, the feasibility of actively bending hardened concrete plates into curved geometries was proven.

4.2 Large-scale bending test #2

Based on the results of the first test, the specimen was optimized to withstand higher prestressing forces without failure. On both supports, the plate thickness was increased and three-dimensional textile reinforcement was installed, is shown in Figure 8. At the support, the point of load introduction of the tendons was...
moved to the neutral axis of the concrete plate, is shown in Figure 9. All these improvements were to reduce the stresses and increase the shear resistance near the supports.

To avoid drilling holes for the screws and thereby possibly damaging the textile reinforcement, the holes were generated by means of placeholders in the formwork. Additional reinforcement was provided at each hole to counteract the weakening of the cross section. Also the reinforcement was replaced by a different AR-glass textile grid (Table 5).

Apart from the aforementioned changes, specimen #2 remained the same as specimen #1: a plate made from textile-reinforced high-strength concrete with the dimensions L/w/h = 500/50/4–8 cm on which steel components for the load introduction of the tensioning force and deviating saddles were attached, is shown in Figure 9.

### Table 5
Mechanical properties of the AR-glass reinforcement used in bending test #2

| Quantity                  | Symbol | Magnitude | Unit   |
|---------------------------|--------|-----------|--------|
| Mass                      | m      | 1,280     | g/m²   |
| Young's modulus           | $E_t$  | 72,000    | MPa    |
| Tensile strength          | $f_t$  | 1,200     | MPa    |
| Fiber cross-sectional area| $A_t$  | 145       | mm²/m  |

---

**Figure 8**  Three-dimensional textile reinforcement cage

**Figure 9**  Detail load introduction area

**Figure 10**  Crack pattern

**Figure 11**  Longitudinal cracks on the face side
To avoid damage due to unexpected stresses during handling, both the top and the bottom of the concrete plate were reinforced. The concrete cover amounted to 5 mm for both the top and the bottom reinforcement layer. Textile reinforcement has a tendency to move out of position during casting due to the buoyancy force exerted by the concrete with its higher density. Therefore, the concrete would be cast in layers upon which the reinforcement was positioned. After the concrete stiffened, another layer would be cast. As a result, the positional accuracy of the textile reinforcement was increased. The experimental procedure was identical to that of specimen #1, see chapter 4.1. The maximum crack width was 0.7 mm on the concrete surface and crack spacing amounted to 5 cm on average, see Figure 10. In the final stages of the test, longitudinal cracks appeared at the level of the reinforcement on the face side, see Figure 11. Subsequently, a large-scale spalling of the concrete cover with an area of ~50 cm × 35 cm in the middle of the test body took place, which led to the failure of the specimen, see Figure 12. A deformation figure in the shape of a circular arc with a smallest radius of curvature of 2.15 m was achieved, is shown in Figure 13.

### 4.3 Large-scale bending test #3

As an alternative to textile reinforcement, a specimen reinforced with steel was investigated, is shown in Figure 14. It was assumed, that large curvatures would be...
achieved by the large strain of the steel reinforcement exhibited during plastic deformation. A test specimen with the same dimensions as that of test #2, see point 4.2, was built. The strength of the reinforcing steel was \( f_y = 560 \text{ MPa} \) with a yield strain of \( \varepsilon_y = 2.8\% \), the maximum plastic strain amounted to \( \varepsilon_u = 100\% \).

The experimental procedure was the same as that of test specimen #1, see chapter 4.1. The maximum crack width was determined to 0.3 mm and crack spacing to 5 cm on average. Failure occurred very early, as the tensile reinforcement yielded only in one place. Therefore, the specimen would not exhibit a constant curvature but a sharp fold at the plastic hinge is shown in Figure 15. The approach of using metallic reinforcement with a plastic material behavior has therefore been deemed unsuitable for actively bent shells.

5 | TEST ON LARGE-SCALE SPECIMEN

Building on the preliminary tests, that have proven the approach of actively bent shells to be feasible, a large-scale investigation was carried out. The aim of this experiment was to bend a 10 m long and 0.65 m wide concrete plate into a simply curved shell. In contrast to the tests described above, the slab is connected to the tendon only at the supports and the middle of the slab is lifted prior to the test.

5.1 | Basics for the erection process-design of the specimen

The approach of active bending investigated so far, tensioning a tied tendon that acts eccentrically onto a plate, enabled the production of shells with a predefined curvature. The structures internal forces and moments result from the dead weight, the geometry, and the force of the tendon.

For the large-scale tests, a tendon connecting the supports was chosen over the previously tested tendons that were connected to the plate. The latter option would have caused unfavorable internal forces due to horizontal thrust, as was described by Widmann. By connecting the supports, the horizontal thrust will be taken directly by the tendon. The shape-generating bending moment...
results from the eccentricity of the tendon force to the neutral axis of the structure. Since the desired deformation figure in this experiment was chosen to correspond to a circular arc, the stiffness of the plate was designed as a function of the internal forces.

The theoretical background for designing plates for active bending is given in Berger et al. Generally, there are two ways to influence the stiffness of textile-reinforced concrete slabs: varying their thickness, and varying their relative amount of reinforcement. To avoid an increased dead weight of the plate, the latter was chosen for the large-scale test.

5.2 Production of the specimen

A textile-reinforced concrete plate measuring $L/w/h = 1.000 \text{ cm}/65 \text{ cm}/3.8–7.8 \text{ cm}$, is shown in Figure 16, was produced. The support regions were strengthened by an increased plate thickness and a three-dimensional

---

**FIGURE 18**  Formwork and reinforcement of the test specimen

**FIGURE 19**  Elevation of the test specimen

**FIGURE 20**  Self-supporting arch with local shape correction

**FIGURE 21**  Final state deformation figure
textile reinforcement cage. The same AR-glass grid\textsuperscript{13} was used as tensile reinforcement as in the large-scale experiment #2, see chapter 4.2.

The goal was to deform the plate into the shape of a circular arc. In order to achieve this with a constant thickness of the plate, it was necessary to grade the reinforcement. It was possible to cover the required reinforcement with two layers of textile grids: a grid layer of minimum reinforcement, which is constant over the span of the plate, and a second grid layer that was designed according to the bending moment distribution and was subsequently graded along the span of the plate. The dimensions of the individual grids are shown in Figure 17. The reinforcement was positioned in the formwork by means individually produced spacers made from fine grain mortar. These were glued to the formwork and the reinforcement. Additionally, wooden bars on the top of the formwork prevented buoying of the reinforcement, is shown in Figure 18.
Due to the great length of the test specimen, overlapping of the reinforcement was required. Special care was taken in a symmetrical arrangement, as any asymmetry would have caused unfavorable deformation figures. The textile grids were connected with cable ties.

For producing 1 m³ fine grain concrete, the following mixture was used:

- Aggregate: 0–4: 1627.6 kg
- Cement: CEM II/A_M(S-L) 42.5 N: 450 kg
- Effective water content: 243 kg (W/B = 0.54).

The concrete’s compressive strength at the time of the experiments, determined on cubes with the dimensions 150 mm × 150 mm × 150 mm, stored according to the environmental conditions, was $f_{cm,cube-26d} = 45$ MPa.

### 5.3 Erection process

The test was conducted 26 days after the plate was cast. The test specimen was raised to install the steel components and the tendon. The pinned support was fixed to the ground with anchors and the other support was equipped with rollers. Steel hinges on both supports assured free rotation. Before the start of the erection process, an initial deformation of the test specimen was executed, as shown in Figure 19. The plate lifted in the center before being tensioned. This caused a higher initial eccentricity of the tendon and subsequently smaller tensioning forces were required to introduce further bending. Thereafter, the erection was conducted by tensioning the tendon with a hydraulic press. As the maximum stroke of the press was 15 cm, multiple lifting operations were conducted.

Early during the erection process, an asymmetric deformation figure developed. Therefore, corrections of the deformation figure were carried out by means of local supports after each stroke of the press, see Figure 20. The success of the experiment was documented by deformation measurements at ten points that were equidistantly placed along the length of the plate. See Section 5.4 for more detailed information.

The radii of curvature achieved in the experiment for all load levels are given in Table 7. For safety reasons, the experiment was stopped at a radius of about 3.5 m, see Figure 21, without failure of the specimen. The maximum strain of the tensile reinforcement amounted to $\varepsilon_t \sim 14\%$, the maximum crack width was less than 0.5 mm. The crack patterns are shown in Figures 22 and 23. By removing the anchoring wedges, the tendon was released and the specimen deformed back to its original shape, a flat plate, is shown in Figure 24.

### Table 6 Linear material parameters for concrete and glass fiber

| Quantity        | Unit | Concrete | Glass fiber |
|-----------------|------|----------|-------------|
| Density         | t/mm³| 2.3e-9   | 2.5e-9      |
| Young's modulus | MPa  | 35e3     | 72e3        |
| Poisson-ratio   |      | 0.2      | 0.22        |

### Figure 26 Deformation figures of the actively bent plate at load level ten determined by means of the FE-analysis (black) in comparison to the experimental investigation (green). FE, finite element
5.4 | Structural analysis

For further design and investigation of actively bent shells, a finite element model was developed and validated using the experimental data from the large-scale test. The model was built using the finite element software ABAQUS CAE 2017. It consists of a plate that spans one-directionally over 10 m with a width of 0.6 m and is supported with hinged connections. The thickness is 38 mm with an increase to 78 mm near the supports. The supports are placed eccentrically to the center-axis of the plate and are moved towards each other to cause the structure to bend into the arc shape.

The concrete plate is modeled as a volumetric body (element type C3D8R) whereas the reinforcement is modeled as a surface-element (element type SFM3D4). The mean dimensions of the mesh elements are 30 by 19 by 300 mm (Figure 25). A smeared-reinforcement formulation was chosen and a perfect bond between concrete and reinforcement was assumed.

The material behavior of the GF reinforcement is modeled as elastic only. Linear material parameters for both materials are given in Table 6. For the material behavior of concrete beyond the limit of elasticity, a concrete damaged plasticity model was added. This general-purpose model may be used for concrete and other quasi-brittle materials (Simulia\textsuperscript{18}). It makes use of the Drucker–Prager yield criterion with extensions made by Lee and Fenves\textsuperscript{19} and Lubliner et al.\textsuperscript{20} A more detailed description of concrete damaged plasticity can be found in Mark.\textsuperscript{21}

The deformed state and the plastic strain of the bent plate are shown in Figure 26 and Figure 27 respectively. With these results closely matching the behavior of the specimen in the experimental investigation, it is assumed that the model may be used to correctly anticipate the deformation and cracking behavior of actively bent structures with more complex geometries and support conditions. Further calibration of the concrete damaged plasticity model by means of additional tests may prove useful to increase the accuracy of the model even more.

5.5 | Test results

The deformation figure of the test specimen was determined by measurements, and is listed in Table 7. For this purpose, the position of ten points which are equidistantly placed along the length of the plate was measured after every load step, see Figure 28. The radius of curvature was evaluated by a circular arc inscribed between the measured positions of two support hinges and the sagitta.

In Table 7, the heights of the individual measurement points are given and evaluated in absolute and relative deviation from the inscribed circular arc. Conclusions of the deformation figure development with regard to a
desired circular arc shape and its symmetry development can be assessed. Up to load step three (R = 8.74 m), the relative deviations are less than 1%, at the last load level 10 (R = 3.91 m) the maximum deviation is relatively 5% and absolutely 21.8 cm.

Additionally, the tendon force was measured with a load cell that was installed at an anchor plate. The measured forces are shown in Figure 29 and are compared to calculated estimates.

The required erection force was very small and amounted to a maximum of 15 kN at the beginning and

**TABLE 7** Arch geometry for load steps

| Step | Radius (m) | $l_i$ (cm) |-4 m | -3 m | -2 m | -1 m | 0 m | 1 m | 2 m | 3 m | 4 m |
|------|------------|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1    | 23.86      | 991        | 17  | 28  | 39  | 47  | 52  | 47  | 40  | 28  | 15  |
|      | ΔR1 (cm)   |            |-1.6| -5.2| -4.6| -2.9| 0.0 | -2.9| -3.62| -5.1| -3.5|
|      | Δ1 (%)     |            |-0.1%| -0.2%| -0.2%| -0.1%| 0.0%| -0.1%| -0.2%| -0.2%| -0.1%|
| 2    | 18.39      | 984        | 30  | 48  | 60  | 66  | 67  | 61  | 54  | 44  | 27  |
|      | ΔR2 (cm)   |            | 6.2 | 5.4 | 3.9 | 1.7 | 0.0 | -3.3| -2.1| 1.5 | 3.4 |
|      | Δ2 (%)     |            | 0.3%| 0.3%| 0.2%| 0.1%| 0.0%| -0.2%| -0.1%| 0.1%| 0.2%|
| 3    | 8.74       | 943        | 46  | 84  | 114 | 133 | 138 | 133 | 117 | 89  | 49  |
|      | ΔR3 (cm)   |            |-1.5 |-3.1 |-1.2 | 0.7 | 0.0 | 0.7 | 1.8 | 2.0 | 0.8 |
|      | Δ3 (%)     |            |-0.2%| -0.4%| -0.1%| 0.1%| 0.0%| 0.1%| 0.2%| 0.2%| 0.1%|
| 4    | 7.23       | 922        | 54  | 95  | 135 | 158 | 165.5| 158 | 138 | 104 | 56  |
|      | ΔR4 (cm)   |            |-3.6 | -9.9 | -3.5 | -1.1| 0.0 | -1.1 | -0.4| -0.5 | -2.1|
|      | Δ4 (%)     |            | -0.5%| -1.4%| -0.5%| -0.1%| 0.0%| -0.1%| -0.1%| -0.1%| -0.3%|
| 5    | 6.29       | 899        | 58  | 108 | 149 | 177 | 189 | 182 | 158 | 119 | 63.5|
|      | ΔR5 (cm)   |            |-6.8 | -10.6| -8.5 | -4.1| 0.0 | 1.0 | 0.6 | 0.2 | -2.3|
|      | Δ5 (%)     |            | -1.1%| -1.7%| -1.3%| -0.6%| 0.0%| 0.2%| 0.1%| 0.0%| -3.7%|
| 6    | 5.21       | 879        | 67  | 124 | 171 | 200 | 210 | 198 | 169 | 124 | 65  |
|      | ΔR6 (cm)   |            |-6.6 | -8.4 | -3.9 | -1.2| 0.0 | -3.2 | -5.5 | -8.0 | -8.6|
|      | Δ6 (%)     |            | -1.3%| -1.6%| -0.8%| -0.2%| 0.0%| -0.6%| -1.1%| -1.5%| -1.7%|
| 7    | 5.02       | 848        | 68  | 129 | 180 | 217 | 233 | 221 | 188 | 138 | 72  |
|      | ΔR7 (cm)   |            |-11.2| -16.7| -13.8| -6.1| 0.0 | -2.1 | -5.2 | -7.9 | -9.6|
|      | Δ7 (%)     |            | -2.2%| -3.3%| -2.8%| -1.2%| 0.0%| -0.4%| -1.0%| -1.6%| -1.9%|
| 8    | 4.58       | 819        | 77  | 145 | 200 | 238 | 252 | 240 | 198 | 143 | 75  |
|      | ΔR8 (cm)   |            |-9.5 | -12.4| -9.2 | -3.1| 0.0 | -1.1 | -11.6| -14.7 | -11.9|
|      | Δ8 (%)     |            | -2.1%| -2.7%| -2.0%| -0.7%| 0.0%| -0.2%| -2.5%| -3.2%| -2.6%|
| 9    | 4.39       | 804        | 79  | 151 | 210 | 250 | 262.3| 245 | 202 | 144 | 74  |
|      | ΔR9 (cm)   |            |-12.7| -13.2| -7.5 | -0.6| 0.0 | -5.5 | -15.6| -19.5 | -15.2|
|      | Δ9 (%)     |            | -2.9%| -3.0%| -1.7%| -0.1%| 0.0%| -1.3%| -3.6%| -4.4%| -3.5%|
| 10   | 3.91       | 754        | 90  | 171 | 235 | 277 | 285 | 263 | 216 | 153 | 79  |
|      | ΔR10 (cm)  |            |-11.1| -6.3 | -0.5 | 4.7 | 0.0 | -8.8 | -19.3| -21.8 | -12.5|
|      | Δ10 (%)    |            | -2.5%| -1.4%| -0.1%| 1.1%| 0.0%| -2.0%| -4.4%| -5.0%| -2.8%|

**FIGURE 28** Deformation measuring points
decreased towards the end of the experiment to 2 kN. It should be noted that some horizontal force results from the rolling friction resistance of the roller support.

6 | OUTLOOK

For a practical application of the presented method, further experimental investigations are required. This applies in particular to methods for increasing the stiffness after erection, for example, sealing and filling the cracks, topping with reinforced concrete, stiffening girders, etc. Furthermore, due to the high slenderness of the construction, stability, and ultimate load investigations are required. Nonlinear finite element calculations are unavoidable for the design of more complex geometries and therefore they have to be worked out accordingly. The goal is to apply this approach also for biaxially curved shells.

7 | CONCLUSIONS

Experimental investigations were conducted to verify the method of actively bending flat plates into shells. During the investigations it was found that, currently, reinforcement with high ultimate strain is only scarcely available. The failure strain of textile reinforcement can vary widely and depends on the application, such as pure roving or roving in concrete. With regard to the concrete to be used, it was recognized that normal concrete is more appropriate than high-strength concrete. Bending tests by tensioning tendons could be carried out successfully, whereby numerous new findings with regard to optimization potential could be gained from experiment to experiment. The test series was completed with a large-scale test on a 10 m long specimen which could be deformed from the plane to a circular arc. Overall, the experiments can be considered as successful and further investigations are planned.

ORCID

Johannes Berger © https://orcid.org/0000-0003-3939-2796
Oliver Gericke © https://orcid.org/0000-0002-7988-2637

REFERENCES

1. Schmidt H. Von der Steinkuppel zur Zeiss-Dywidag-Schalenbauweise. Beton- und Stahlbetonbau. 2005;100:79–92.
2. Hawkins W et al. Flexible formwork technologies – A state of the art review. Struct Concrete. 2016;17:911–935.
3. Veenendaal D, West M, Block P. History and overview of fabric formwork: Using fabrics for concrete castig. Struct Concrete. 2011;12:164–177.
4. Curbach M, Haptenbuchner B, Ortlepp R, Weiland S. Textilbewehrter Beton zur Verstärkung eines Hyparschalentragwerks in Schweinfurt. Beton- und Stahlbetonbau. 2007;102:353–361.
5. Scholzen A, Chudoba R, Hegger J. Thin walled shell structures made of textile-reinforced concrete. Struct Concrete. 2015;16:106–114.
6. Hegger J, Curbach M, Stark A, Wilhelm S, Farwig K. Innovative design concepts: Application of textile reinforced concrete to shell structures. Struct Concrete. 2018;19:637–646.
7. Kromoser B, Kollegger J. Pneumatic forming of hardened concrete – Building shells in the 21st century. Struct Concrete. 2015;16:161–171.
8. Sobek W. Concrete shells constructed on air-supported formwork. Bauingenieur. 1991;66:545–550.
9. Lienhard J, Knippers J. Biegeaktive Tragwerke. Bautechnik. 2015;92:394–402.
10. Lienhard J, Gengnagel C, Knippers J, Alpermann H. Active bending, a review on structures where bending is used as a self-formation process. Int J Space Struct. 2013;28:187–196.
11. Berger J, Feix J, Gericek O, Sobek W. Actively bent concrete shells. Struct Concrete. 2020.
12. Kulas C-H. Zum Tragverhalten getränkter textiler Bewehrungselemente für Betonbauteile [PhD thesis]. Lehrstuhl und Institut für Massivbau der RWTH Aachen; 2013.
13. Solidian GmbH, Germany. Technisches Datenblatt, Solidian GRID Q145/145-AAE-25.
14. Solidian GmbH, Germany. Technisches Datenblatt, Solidian GRID Q142/142-CEE-25.
15. Kromoser B, Kollegger J. Active bending of hardened concrete plates for the construction of spatially curved surfaces. Beton- und Stahlbetonbau 112. Heft. 2017;2:106–115.
16. Backstein Engineering GmbH, Germany. Typ 66, AR Glasfasertextil, 612g/m². www.moertelshop.com
17. Widmann R. Biegeaktive Betonstrukturen. [Master thesis]. Arbeitsbereich Massivbau und Brückenbau, Universität Innsbruck; 2019.
18. Simulia DS. Materials. ABAQUS analysis user’s manual. Vol III. Providence, RI: Dassault Systemes, 2014.
19. Lee J, Fenves GL. Plastic-damage model for cyclic loading of concrete structures. J Eng Mech. 1998;124:892–900.
20. Lubliner J, Oliver J, Oller S, Oñate E. A plastic-damage model for concrete. Int J Solids Struct. 1989;25:299–326. https://doi.org/10.1016/0020-7683(89)90050-4.

21. Mark P. Zweiachsig durch Biegung und Querkräfte beanspruchte Stahlbetonträger (Habilitation) [PhD thesis]. Institut für Konstruktiven Ingenieurbau, Universität Bochum; 2006.

AUTHOR BIOGRAPHIES

Johannes Berger, Unit of Concrete Structures and Bridge Design, University of Innsbruck, Innsbruck, Austria.

Oliver Gericke, Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart, Stuttgart, Germany.

Jürgen Feix, Unit of Concrete Structures and Bridge Design, University of Innsbruck, Innsbruck, Austria.

Werner Sobek, Institute for Lightweight Structures and Conceptual Design (ILEK), University of Stuttgart, Stuttgart, Germany.

How to cite this article: Berger J, Gericke O, Feix J, Sobek W. Experimental investigations on actively bent concrete shells. Structural Concrete. 2020;21:2268–2281. https://doi.org/10.1002/suco.202000045