A concrete solar collector – From design to assembly in full scale

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Introduction

Concentrating solar power (CSP) generation makes use of direct solar radiation by focusing it via mirrors on a focal line (parabolic trough, Fresnel) or a focal point (solar towers), heating a heat transfer medium which is used in a power block to generate electricity. In most of the power plants, especially recently constructed ones, a heat storage is included so that electricity can be supplied for several hours after sunset. The thermal storage is charged by surplus heat from the solar field during sunny hours of the day and is later discharged to operate a turbine at the desired time adapted to the demand. Additional fuel back-up firing can further extend the flexibility of such power plants.

Today the operational capacity of CSP is around 5 GW (Figure 1) worldwide. Thus it is a technology still at the beginning of the learning curve compared to other technologies as e.g. PV with 304 GW. Parabolic trough collectors have widely been used in CSP plants and nowadays their efficiency is quite far developed leaving few room to optimize their thermal output. Therefore the main focus is now on investment cost reduction and on lowering non-technical costs.

A recent example of significant cost reduction was presented in Sep. 2017 in Dubai, where a consortium was the preferred bidder for the 700 MW combined tower and trough station DEWA IV, at a PPA price of USD 0.073 per kWh (AED 0.27 per kWh) [1, 2]. This includes a thermal storage allowing turbine operation for 10 hours. Due to a long PPA duration of 35 years, very good financing conditions, production guarantee conditions, it is found that the technology costs are low [3].

Clearly the reduction of investment costs is one important way to lower the Levelized Costs of Electricity (LCOE). The ConSol project therefore aimed at reducing the investment costs with the idea of replacing steel structures by concrete components.

Conceptual design of a concrete collector

The conceptual design of the concrete collector is leaned on the geometrical characteristics of the already existing steel collector EuroTrough [4, 5] with an aperture width of 5.77 m and a length of 12.00 m. The structural system and bearing conditions are adopted from a first small-scale concrete prototype (Figure 2) with an aperture width of 2.205 m and a length of 3.20 m, which has been built up within a cooperative project between the TU Kaiserslautern and the Ruhr University Bochum [6, 7]. It shows the general feasibility of line-like concentrating solar collectors made from concrete merging the supporting and reflecting (so directly supporting the mirrors) structure to a parabolic shell [8, 9]. It exhibits a mean shell thickness of 2.5 cm. The design significantly depends on the concrete’s high tensile strength, as cracking would cause soften-
scales up the prototype by a magnitude of four. The non-cracked shell allows only small deformations to fulfill the demands on accuracy for the solar concentration. Furthermore, the prototype is characterized by a novel bearing concept which serves as the bearing structure and simultaneously tracks the sun, while the centre of gravity stays on a horizontal line [10]. This means, that almost no mechanical work – just overcoming friction and geometric uncertainties – with respect to self-weight is needed to move the collector during the course of the day. In the longitudinal direction the system of the module can be interpreted as a single span girder with two cantilever arms.

In the framework of the 6th Energy Research Programme of the Federal Government funded by the Federal Ministry for Economic Affairs and Energy, seven partners comprised of scientific research institutions and industrial partners (Table 1) under the leadership of the German Aerospace Center (DLR) developed within the interdisciplinary project ConSol (“Concrete Solar Collector”) a holistically optimized collector made from concrete in full scale. The collector concludes an optimized design of the shell, the supporting structure, the driving system and mirroring. It scales up the prototype by a magnitude of four. Moreover, it is fully equipped and workable to be included in a power unit.

**Structural and material design restrictions**

The ConSol prototype collector was built up of different precast concrete components to ensure a fast assembly on site. It is composed of two modules which share an engine in between. Each of the two modules consists of a shell, two sickles, two axial rocker bearings, two upper gears, two lower gears with a running surface and two middle sleeve foundations. Both modules share a drive bearing and two edge sleeve foundations. Figure 3 illustrates the two shells with substrutures in an exploded drawing.

Due to manufacturing demands of the of the prototype that should be produced in simple formworks, a one-walled shell with a constant cross-section is chosen. Thus, the torsional stiffness compared to ordinary steel framework modules that comprise an additional torque tube is pronounced smaller. Therefore, the driving system of the collector is designed to move only two modules, one per shell side, to minimize torsion by the drive. Considering longer collector lengths, several driving systems have to be installed and even more important synchronized to a simultaneous motion. The driving system is installed on a special drive bearing between two modules. It is attached to sickles with a lower circular shape that are connected to the shell and enable the movement of the collector. Hence, the collector consists of two shells, which both can be interpreted as a one span girder of 8 m with a cantilever arm of 4 m in longitudinal direction. Almost every structural part of the collector is built of precast elements connected to each other. Additionally, mounting parts with respect to the connections of precast elements and for external installations, e.g. the absorber tube’s support and the driving system’s pins, were necessary. Therefore, a 3-dimensional BIM (Building Information Modelling) model [11] (cf. Figure 3) has been developed to ensure an integrated design, to tackle collision queries between the elements and to include all geometrical as well as material data and other mechanical properties.

The components are made of two different types of concrete. For the sleeve foundations and rocker bearings serves a standard concrete C30/37. For elements with high demands on accuracy and/or bearing capacity, a high-performance concrete based on the binder pre-mixture NANODUR® [12] was necessary. The concrete exhibits a very dense microstructure and a high compressive strength as well as a high tensile strength. Furthermore, the concrete has a good workability due to high fluidity and a self-compacting behaviour. The principal material properties are given in Table 2.

The design of parabolic trough collectors strongly depends on the specific inherent and environmental actions on the modules. They mainly result from self-weight and wind loads that both differ with respect to the collector’s position during the course of the day. Thus, a lot of varying load situations occur due to the sun tracking. Additionally and only for the here presented prototype, a snow load was additionally assumed, since the collector is assembled in Borchen, Germany. In typical locations of solar collectors, high temperatures and severe solar irradiation dominate making snow load assumptions unnecessary. The self-weight is applied proportional to the shell thickness and snow according to standard code regulations. The specific wind loads have been derived

**Tab. 1. Project partners of ConSol.**

| German Aerospace Center (DLR), Cologne | 
| Solarlite CSP Technology GmbH, Duckwitz | 
| Pfeifer Seil- und Hebetechnik GmbH, Memmingen | 
| Stanecker Betonfertigteilwerk GmbH, Borchentort | 
| ALMECO GmbH, Bernburg | 
| Technical University of Kaiserslautern, | 
| Kaiserslautern | 
| Ruhr University Bochum, Bochum | 

**Tab. 2. Material properties of the used NANODUR® concrete.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>E₀ₚ</td>
<td>52,700</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>f₀ₚ</td>
<td>139.4</td>
</tr>
<tr>
<td>Bending tensile strength (average and characteristic values)</td>
<td>fₕₚₚ</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>fₕₙ</td>
<td>15.5</td>
</tr>
<tr>
<td>Tensile strength (average and characteristic values)</td>
<td>fₚₚₚ</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>fₚₙ</td>
<td>8.0</td>
</tr>
<tr>
<td>Density</td>
<td>ρ₀</td>
<td>2,440</td>
</tr>
</tbody>
</table>
from particular wind tunnel experiments [13]. Three different states with respect to the wind speed have to be considered:

- Operational state, where the collector tracks the sun under low wind speed conditions (v ≤ 10 m/s)
- Transition state, where the collector is moved to a safety position under upcoming moderate wind speed conditions (v ≤ 15 m/s)
- Survival state, where the collector holds in a constant survival position under strong wind speed (v ≤ 33 m/s)

In state (1) and (2) the collector’s orientation is variable. The collector’s position of state (3) corresponds to the deflection with the lowest aerodynamic wind load coefficients being the zenith position with the opening facing vertically upwards. In operational state (1) the serviceability of the shell is ensured by means of accuracy demands to ensure full solar concentration in all positions. Thereby, the deformations of the shell are limited by means of the resulting waviness of the surface. The transition (2) and the survival state (3) are the main states for the design in ultimate limit state (ULS), where its robustness is guaranteed due to reinforcement. In addition, serviceability is provided by limiting the first principle stress to a reduced share of the characteristic tensile stress $\sigma_t$ of the concrete to achieve a (computationally) non-cracked state.

**Shell design**

The design of the shell can be divided into an outer and inner form finding process aiming for a robust, low-weight structure but high stiffness. The outer form finding ensures a full solar concentration by determining the cross section of the shell restricted by accuracy and material demands. The inner form finding ensures robustness by means of the reinforcement design. Therefore, the shell with outer sickles was numerically built up as a parameterized Finite-Element model consisting of 4-noded shell elements with 6 degrees of freedom per node. Due to the central symmetry, only one module was modelled (Figure 4). The outer sickles have a radius of 2.10 m. The focal length – the distance between the parabola vertex and the focal point where the receivers are arranged – corresponds to 1.71 m defining the curvature of the parabola.

The thickness of the shell was designed to only 4.5 cm in average. A maximum waviness criterion of the surface serves as a restriction for the design. This holds true, as a surface deflection causes twice as much solar ray deviations. The criterion is derived from empirical values of the Euro-Trough collector [14] and it is defined by the root mean square of the slope deviations $SD_{x,rms}$ being the deviation between the slope values of the undeformed parabola and the load induced distorted parabola – over the surface of the shell. It is limited to 2.0 mrad. It should be noted, that it has to be fulfilled only in transverse direction, since deviations in longitudinal direction deflect the solar rays just along the absorber tube. This does not prevent rays to meet the tube. Therefore, the deformation of the surface in operational state (Figure 5, top) and the resulting slope deviations $SD$ (Figure 5, bottom) for the dominating load situation were determined. A rotation of 45° is assumed. Figure 5 shows the results of the accuracy analysis for the developed optimized design with a decreasing shell thickness of 5.5 cm at the vertex to 3.5 cm at the edge of the cross section. It results into a root mean square of 2.08 mrad that seems acceptable for a first full scale prototype. Additionally, the tensile strength criterion is continuously maintained over the shell.

For the reinforcement a single-layered, standard steel mesh is chosen for economic reasons. It was designed from a superposition analysis of maximum and minimum sectional forces resulting from the load situations in transition and operational state. A mat Q257 is chosen that provides 2.57 cm²/m reinforcement area crosswise. A concrete cover of only 1 cm suffices against environmental impacts due to the dense structure of the high-performance concrete. Additional reinforcement is required at locally high stressed areas. These areas lie at the borders of the shell, especially next to the middle bearing due to bending in longitudinal direction and at the end of the sickles. No shear reinforcement is required.

The sickles below the shells enable the movement of the superstructure. They are connected to the shell by a two component adhesive and threaded rods. Therefore, special mounting parts of steel are installed into the shell. To avoid slipping or tipping while tracking the sun, a novel gear is installed parallel to the sickle and vice versa on the axial rocker bearings. It is shaped with teeth and is made from high-performance concrete (cf. Figure 9).

**Substructure with rolling up concept**

Every shell is placed on two bearings that are held by sleeve foundations. Threaded rods and mortar grouting ensure a solid connection. Fluting between the single parts strengthen the composite. Two different types of foundations are fabricated. Two foundations of a first type are installed at the interconnection of the two shells including the drive bearing. The other type corresponds to the middle sleeve foundation which is indented from the edge of the shell (cf. Figure 3). All sleeve foundations rest on block foundations with threaded rods to keep a gap of about 5 cm. This allows adjusting the substructure to a constant horizontal level, necessary for a precise solar tracking.

The movement of the collector is described by an unrolling of the shell along the rocker bearings. Doing so, the centre of gravity of the superstructure remains on a constant horizontal level. Therefore, sickle and rocker bearing need corresponding geometrical shapes. The sickle exhibits a circular shape, the rocker bearing the one of a shortened cycloid. Figure 6 shows the kinematics of tracking. The centre of gravity (red point) follows a horizontal line. Moreover, it remains in a pure vertical offset to the contact point.
to the rocker bearing. Consequently, no torsional effects occur from self-weight and very economic engines can move the shells, despite its quite large dead load.

**Power unit and motions**

The power unit consists of an electric engine of 180 W, chains, several rollers and interconnections to the drive bearing. A longitudinal shaft harmonises the tracking from shell to shell and avoids offsets. Figure 7 shows the components in an exploded drawing. It should be noted that very robust components are chosen and the energy demand – compared to the pronounced self-weight of the two shells of about 20 tons – remains very limited.

The tracking in operational slow speed mode works automatically with a high precision of $<0.1^\circ$ [15] and a precise drive speed in the range of 10°/h to 15°/h. An angle sensor attached to one sickle measures the actual deflection and in case of a deviation between the correct and actual position of more than 0.05° the system repositions the shell. Table 3 summarizes the relevant technical data of the drive system.

**Detailing and realisation of a large-scale prototype**

The prototype collector composed of two modules was built in Borchen near Paderborn (Germany). It comprises eight different precast concrete components with variable quantities and two different types of concrete (Table 4). Each of the two modules consists of a shell, two sickles, two axial rocker bearings, two upper gears, two gears with a running surface and two middle sleeve foundations and share a drive bearing as well as two edge sleeve foundations (cf. Figure 3). The whole collector weighs about 40t, whereby the unrolling superstructure of one module has a weight of almost 10t.

The manufacturing process can be divided into two parts, namely the manufacturing of the substructure, mainly the bearings and foundations, and the fabrication of the shell superstructure.

**Rocker bearings and foundation**

The substructure consists of the block foundations, the rocker bearings with integrated concrete gears and the running surface as well as the bearing of the drive system. In order to manufacture the six sleeve foundations, three wooden formworks (two for the middle foundations, one for the edge foundation) were needed (Figure 8, (1)). All parts have a width of 1.40 m and lengths of 1.00 m at the middle foundations and 1.10 m at the edge foundations. They are designed for a usual soil pressure of sands or gravel. The edge sleeve foundations exhibit three gaps of 17 cm for the rocker and the drive bearings, while just one gap for the axial rocker bearing suffices for the middle sleeve foundations. All gaps were lined with a riffle sheet to increase the roughness. Figure 8 (2) shows the completed foundations with ver-

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**Tab. 3. Technical data of the drive.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driveway length</td>
<td>4.40</td>
<td>m</td>
</tr>
<tr>
<td>Total angular movement</td>
<td>+80 zenith -80°</td>
<td>°</td>
</tr>
<tr>
<td>Rotation speed (slow speed mode)</td>
<td>10 to 15</td>
<td>°/h</td>
</tr>
<tr>
<td>Rotation speed (fast speed mode)</td>
<td>7</td>
<td>°/min</td>
</tr>
<tr>
<td>Nominal driving force</td>
<td>20</td>
<td>kN</td>
</tr>
<tr>
<td>Maximum driving force</td>
<td>40</td>
<td>kN</td>
</tr>
<tr>
<td>Holding force</td>
<td>90</td>
<td>kN</td>
</tr>
<tr>
<td>Power consumption</td>
<td>0.6</td>
<td>W/max</td>
</tr>
<tr>
<td>Protection class</td>
<td>IP65</td>
<td></td>
</tr>
</tbody>
</table>

**Tab. 4. Overview of the produced prototype precast elements.**

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Quantity</th>
<th>Concrete material</th>
<th>Mass per element [kg]</th>
<th>Total mass [t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Edge sleeve foundation</td>
<td>2</td>
<td>C35/4S</td>
<td>1,400</td>
<td>2.80</td>
</tr>
<tr>
<td>2</td>
<td>Middle sleeve foundation</td>
<td>4</td>
<td>C35/4S</td>
<td>1,550</td>
<td>6.20</td>
</tr>
<tr>
<td>3</td>
<td>Lower gear with running surface</td>
<td>4</td>
<td>Nanodur®</td>
<td>750</td>
<td>3.00</td>
</tr>
<tr>
<td>4</td>
<td>Sickle</td>
<td>4</td>
<td>Nanodur®</td>
<td>560</td>
<td>2.24</td>
</tr>
<tr>
<td>5</td>
<td>Upper gear</td>
<td>4</td>
<td>Nanodur®</td>
<td>290</td>
<td>1.16</td>
</tr>
<tr>
<td>6</td>
<td>Axial rocker bearing</td>
<td>4</td>
<td>C35/4S</td>
<td>1,480</td>
<td>5.92</td>
</tr>
<tr>
<td>7</td>
<td>Drive bearing</td>
<td>1</td>
<td>C35/4S</td>
<td>2,050</td>
<td>2.05</td>
</tr>
<tr>
<td>8</td>
<td>Shell</td>
<td>2</td>
<td>Nanodur®</td>
<td>8,640</td>
<td>17.28</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td>25</td>
<td></td>
<td></td>
<td>40.65</td>
</tr>
</tbody>
</table>
crete was only used for the high-loaded parts with specific accuracy demands such as the running surface and the gear of the axial rocker bearing. Here, increased tensile and compressive strengths as well as accurate surfaces and shapes are required. Figure 8 (3) shows the formwork for the running surface and the gear. Due to the mainly curved surfaces of this element, a formwork of extruded polystyrene was used. It was cut by a 3D heating wire steered by a CAD model to achieve high precisions (<1 mm). For the connection to the rocker bearing made from normal concrete, the running surface additionally provides stirrup starter bars. Upon completion of the running surface and the gear, the component was used as a formwork element for the axial rocker bearing (Figure 8, (4)). Further parts of the formwork were made of wood and extruded polystyrene (for the notches). Within the starter bars, a monolithic composite construction between the already concreted running surface and the axial rocker bearing could be realized. The completed rocker bearings have a length of 5.34 m, a height of 2.04 m and a thickness of 15 cm (Figure 8, (5)).

The sickles and the upper gears were made from high-performance concrete solely. Sickle and gear have a width of 3.45 m and a thickness of 15 cm for the sickle and 8 cm for the gear, respectively. Sickle and upper gear were manufactured as single elements and connected afterwards. So, both parts had to be produced geometrically accurate at the connection faces. Therefore, special steel parts were manufactured and encased in the concrete to ensure a necessary tolerance of 1 mm. The sickle including running surface and the upper gear were built using extruded polystyrene formwork (Figure 9, (1)). The upper gear (Figure 9, (2)) was installed on top of the sickle and connected by threaded rods with a certain gap to avoid collision queries between the gear of the rocker bearing and the sickle and vice versa (Figure 9, (3)). A stainless steel sheet with a thickness of 1 mm was installed along the surface of the sickle to protect the concrete from abrasion and wear. Finally, the drive bearing was built. Except for two notches to save material costs, no polystyrene elements were needed and the formwork was completely made of wood (Figure 9, (4)). The component has a width of 4.77 m, a thickness of 12 cm and a maximum height of 2.76 m (Figure 9, (5)). Several transport anchors were placed for the subsequent installation of the drive system.

Shell superstructure
The superstructure consists of the shell and the outer sickles with connected concrete gear segments. Sickles and gear segments were manufactured along the substructure components. The primary demand on the shell was a precise surface, so the shell was cast with its inner surface downwards. Therefore, the concreting could be done from the backside of the shell, where no accuracy demands with respect to solar concentration have to be fulfilled. The formwork was made from plywood, while the downside part was covered with steel sheets to ensure the precise surface (Figure 10, (1, 2)). Onto the sheets, the reinforcement with spacers of 1 cm (Figure 10, (3)) and the additional mounting parts were placed. The shell was cast along the apex at the top of the formwork. After concreting and hardening, the counter formwork was removed and the shell lifted out of the bottom formwork. This was done over 8 mounting anchors, 4 in each axis of the sickles, by two indoor cranes (Figure 10, (4)). Then, the outer
sickles with already attached concrete gears were connected to the shell by threat-
ed bars and an additional layer of two-com-
ponent adhesive to provide a full connec-
tion between sickles and shell (Figure 10, (5)).

Assembly on site and performance evaluation of the collector

For assembly, all elements and structural parts have to be installed with enhanced accuracy, since uncertainties of single parts would sum up. This could lead to losses in solar concentration or even avoid operation due to different heights of bearings. Therefore, the block foundations were ex-
actly aligned on the prepared and levelled working panel (Figure 11, (1)). Afterwards, the six sleeve foundations were placed on the block foundations that con-
tain the necessary threaded rods fitting into the cladding tubes. A steel template cut by waterjet was set in the block founda-
tions to provide the exact position of the threaded rods. Then, the axial rocker bear-
ings and the drive bearing were installed (Figure 11, (2)). They were placed in the gaps of the corresponding sleeve foun-
dations and fixed by horizontal threaded rods. After levelling the substructure, the gaps between the bearings and sleeve foundations were filled with mortar. Before placing (Figure 11, (3)), both shells had to be turned around, since the concret-
ing was done upside down. Therefore, the outer sickles with already attached gears were mounted onto the shells (Figure 11, (4)) and auxiliary steel frames were attached (Figure 11, (5)). It should be noted that this process only occurs for the prototype. In serial production, alter-
natives have to be considered, like a form-
work with integrated tilting table to auto-
matically flip the shell during manufactur-
ing. Here, the shells are finally placed on top of the bearings and the drive engine is installed at both modules to ensure stabili-
ity as well as the ability of suntracking. Ta-
ble 5 summarizes the basic technical data of the collector.

The receiver tubes, three per module, with their brackets were subsequently attached to the shell. In the framework of the pro-
ject, a new mirror material made from electrochemical polished aluminium strip with a thickness of 0.4 mm with a silver based multilayer PVD coating and an ad-
ditional sol-gel protective coating with a solar weighted specular reflectivity of
92.3 %, has been developed by the Almeco company and glued to the concrete surface by adhesive tape (Figure 11, (6)). Un-
like conventional parabolic troughs, where a multitude of modules is arranged to a solar field, the here presented prototype is not utilized for standard power genera-
tion, since the overall aperture is not suf-
ficient for this. Nevertheless, the collector is connected to a water circulation to demons-
trate its effectiveness by heating up wa-
ter that is pumped through the receiver. Figure 12 shows the complete collector.

To specify the optical efficiency, the collect-
or was measured by digital close range photogrammetry, which is a common tool to evaluate surface qualities of parabolic
Conclusions

The interdisciplinary research project has shown the general feasibility of a fully equipped and workable concrete trough collector with an overall aperture area of 138.5 m², which was developed and assembled within 2.5 years. The parabolic shell made from high-performance concrete was designed with a mean thickness of 4.5 cm and mesh reinforcement by means of outer and inner form finding. The supporting structure consists of rocker bearings for suntracking. Concrete gears with specifically designed teeth avoid tipping. The drive system of the collector consists of a power engine with 180 W only to drive two modules with a total weight of about 20 t. Additional collectors with similar driving systems can easily be integrated by means of a shaft synchronizing the modules. The collector was covered with a newly developed mirror material made from chemical polished aluminium strip with a silver based multilayer PVD coating and an additional sol-gel protective coating with a solar weighted specular reflectivity of 92.3%. By means of digital close range photogrammetry the shell was measured and an intercept factor of up to 85.6% was gained, assuming a corrected receiver position.

Costs for electricity output with respect to a reference solar power plant result to 21.9 €/kWh which is – for this single prototype – not yet fully competitive. Minimization of material efforts, a heat treatment to prevent drying by shrinkage and elaborations in the driving and mirroring system are improvement examples. Concrete proved to be an appropriate material for sustainable solar structures.

Acknowledgment

The authors thank the German Federal Ministry for Economic Affairs and Energy (BMWI) for the financial support of the project “ConSol – Concrete Solar Collector” in the framework of the 6th Energy Research Programme on the basis of a decision by the German Bundestag.

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