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Design of modular concrete heliostats using symmetry reduction methods

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Abstract

In Concentrated Solar Power (CSP) plants the incident solar radiation is focused onto a receiver by means of collectors. A fluid is heated up and in a downstream power block electricity is generated. In point-focusing solar towers, the solar concentration is achieved by so-called heliostats that are arranged to a solar field. In this contribution, the development of concrete heliostats with circular shapes and an aperture area of 30 m² is presented. A high-performance concrete with high tensile and compressive strength values is used. The circular structure is dissolved into identical but symmetrically reduced modules derived from system reduction methods. For designing, the tensile strength of the concrete is restrictive to ensure linear-elastic material behavior and to avoid softening by cracking. After dimensioning, the derived equivalent plate is converted into strut-like structures possessing equal stiffnesses with respect to the partial module size. These modules are circularly post-tensioned to form a heliostat. Numerical investigations of the modules prove their accuracy. A full solar concentration, that is, the reflected solar radiation is completely focused on the receiver, is achieved. Due to the multitude of modules within a solar field, serial production with integrated quality control is recommended.

KEYWORDS

concentrated solar power, heliostat, high-performance concrete, modular structure, symmetry reduction

1 | INTRODUCTION

1.1 Heliostats for concentrated solar power plants

Concentrated solar power (CSP) is a relatively young technology with an installed power of 4.5 GW worldwide.¹ In CSP plants, the incident solar radiation is focused onto a receiver. At the receiver, the solar radiation is bundled to heat a fluid. This fluid is used to produce steam in a downstream power block, where electricity is generated through a turbine. In combination with thermal energy _____

storage, it is an alternative to conventional power plants. Next to parabolic troughs that belong to line-like focusing systems, one of the most promising technologies for CSP plants are point-focusing solar power towers. The solar concentration hereby is achieved by a multitude of mirroring collectors, so-called heliostats. These heliostats track the sun biaxially and are arranged around a central tower where the receiver is located (Figure 1, left). Process temperatures of around 700°C are achieved. For the point-wise concentration of the solar radiation, the mirror surfaces have the shape of flat paraboloids. Hence, the efficiency is mainly dependent on the accuracy of the mirror shape.

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FIGURE 1 Solar power tower pilot plant in Jülich, Germany with detail of a heliostat (left), and Stellio heliostat⁶ (right) source: Left: German Aerospace Center (DLR), right: sbp sonne GmbH

Typically, heliostats are built up as so-called T-type structures consisting of a steel structure and glass mirror facets. The mirror elements are supported by cross beams that are mounted to a torque tube. The torque tube and the pylon form the "T" (cf. Figure 1, left). Doing so, deformations of the cross beams and the torque tube superimpose. However, a multitude of heliostat concepts exists, for example, steel frameworks or sandwich facets.² They mainly aim for cost reductions since the heliostats represent about 40% of the total CSP plant investment costs.³ Thereby, not only the supporting structure but also the mirrors, bearing materials, foundations, drives, and installation are topics of ongoing research. An overview is given by *Pfahl et al.*⁴

One of the most advanced heliostat with respect to efficiency and costs is the so-called Stellio developed by schlaich bergermann partner (sbp).⁵ The pentagonal concentrator is supported by radial cantilever arms and a central mount⁶ (Figure 1, right). Thereby, the load path is reduced compared to T-type heliostats. Moreover, the steel framework cantilever arms are evenly utilized. This design is characterized by a low mass structure with a high optical accuracy, which serves as a benchmark in this contribution.

1.2 | Conceptual design of modular concrete heliostats

A first known concrete heliostat is shown, among others, in the review provided by *Pfahl.*² It is made from regular concrete and possesses thicknesses in the range of decimeters. For sun tracking, this concept requires a support and rotation axis in the center of gravity, so that a massive counter weight was necessary. However, for parabolic troughs, it could be shown that slender light-weight shells made from high-performance concrete (HPC) are an economic alternative to conventional collectors due to the low costs of concrete.^{7,8} HPC is characterized by a high compressive strength of approximately >70 to 80 MPa and an increased durability compared to regular concrete.⁹



FIGURE 2 Conceptual design of a modularized, post-tensioned strut-like heliostat made from concrete

heliostats. This goes along with higher accuracy demands. Moreover, shell-like collectors¹⁰ that are appropriate for parabolic troughs will now be dissolved in strut-like structures. Thereby, the statical height is increased to ensure higher stiffness.¹¹

The conceptual design of the HPC heliostats is orientated at the Stellio collector. A central mounted structure with main radial beams is chosen. For the bearing that is arranged in the structure's center of gravity, an inner ring is formed, where the radial beams are connected transferring the loads, that is, self-weight and wind loads, to the support. The whole heliostat also exhibits a circular shape allowing a compact field layout and minimizes the mutual shading of heliostats in the solar field. In comparison, the corner areas of rectangular concentrators might shade parts of concentrators located behind (cf. Figure 1, left). A circumferential post-tensioning is used to compress the strut structure utilizing the high compressive strength of the used concrete.

It minimizes or even avoids reinforcements, as discussed for axially compressed columns by *Schmidt and Curbach*.¹² Therefore, an outer ring is necessary to apply the tensioning forces. Secondary struts are added for the transfer of forces to the support but also to bear mirror elements or for stability purposes of the radial and outer beams. Due to the rotationally symmetric shape, the heliostat is designed by system reduction methods.^{13,14} Hence, the structure can be modularized in equal partial segments which are held together by post-tensioning. The conceptual design of the heliostat is illustrated in Figure 2 for an exemplary modular structure made from 8 modules. It exhibits a diameter of 6 m which results in a mirror area of around 30 m² and lies in the range of cost-optimized mirrors.^{3,15}

2 | DEVELOPMENT OF PARTIAL STRUCTURES USING SYMMETRY REDUCTION

2.1 | High-performance concrete (HPC)

The heliostats will be made from HPC based on the binder Nanodur compound 5941 which has two crucial advantages for the design. First, the Young's modulus E_C is much higher than for regular concrete. Thereby, low deformations are secured. Second, also the compressive and, even more important, the tensile strength are much higher. Due to the compressive strength, the post-tensioning stresses can be sustained. The high tensile strength is necessary to ensure a non-cracked state I. This is crucial since softening by cracking would cause enlarged deformations and thus endanger a precise solar concentration. In previous designs of concrete shell collectors for parabolic troughs, the Nanodur concrete has proven to be suitable.^{7,11} It exhibits good workability and has self-compacting behavior and high durability.¹⁶ The material properties differ with respect to the used aggregates and additives. However, the Young's modulus used for all analytical derivations is set to 47.500 MPa which is a more or less a conservative lower value. The mean flexural tensile strength could be determined to $f_{ctm,fl}$ = 20 MPa in 3-point bending tests using prisms with dimensions of 40/40/160 (mm) according to DIN EN 196-117 and DIN EN12390-5.¹⁸ The age of the concrete prisms was 28 days with water storage of 27 days. According to Schmidt,¹⁹ it is transferred to the axial tensile strength and, based on the scattering data of the tests, the characteristic 95% quantile value is calculated to $f_{ctk,95}$ = 8.2 MPa. For dimensioning, the first principle stress of the concrete is limited to a share of the axial tensile stress which is diminished by the endurance coefficient a_{ct} of 0.8²⁰ and results to 6.6 MPa. Additionally, the compressive strength has also been determined in experiments to f_{cm} = 116 MPa. Therefore, it is not classified as an Ultra-High Performance Concrete (UHPC). The basic material properties for the design are summarized in Table 1. The experimental data is based on a concrete mixture consisting of Nanodur Compound 5941 (1050 kg/m³), sand 0/2 (430 kg/m³), basalt grit 1/3 (880 kg/ m³), water (155 kg/m³), superplasticizer Glenium ACE 430 (14 kg/m³), and shrinkage reducer Eclipse Floor (6 kg/m³).

TABLE 1Material properties of Nanodur concrete for theanalytical and numerical design of concrete heliostat structures

Material property		Value	Unit
Mean Young's modulus	E _{cm}	47.500	MPa
Mean compressive strength	f _{cm}	116	MPa
Mean flexural tensile strength	f _{ctm,fl}	20	MPa
Mean axial tensile strength	f _{ctm}	10.2	MPa
Axial tensile strength	f _{ctk,95}	8.2	MPa
	$\alpha_{ct} f_{ctk,95}$	6.6	MPa
Density	ρ _c	2.500	Kg/m ³



FIGURE 3 Relationship of the focal length with the height of a paraboloid for a radius *R* = 3 m

2.2 | Geometry and accuracy demands

The shape of the reflecting surface of a heliostat is an elliptical paraboloid. For a circular structure, it corresponds to the surface of a parabola rotated around its axis of symmetry (z-axis). The shape of the parabola is defined by its focal length *f*, which describes the distance to the so-called focal point. In simplified terms, the focal length corresponds to the distance between the heliostat and the receiver at the central tower (cf. Figure 3). With r as the radial coordinate, the curve z(r) of the paraboloid is given by:

$$z(r) = \frac{1}{4f}r^2 \tag{1}$$

with
$$z(r = R) = h = \frac{1}{4f}R^{2}$$

In Figure 3 the height *h* of the heliostat's surface with respect to *f* is illustrated for a radius of R = 3 m. For small values of *f*, the height h of the paraboloid is increasing and vice versa. Additionally, it can be noticed that for an increasing *f* the differences in height are decreasing.

In a solar field, the different positions of the heliostats would require individual shapes. However, similar shapes of heliostats can be summarized into group arrangements. A coarse classification is shown in Figure 3. For almost equal differences of height ($\Delta h \approx 2$ cm), the mean heights of these ranges are chosen and lead to focal lengths of 36, 60, and 138 m (Figure 3). This classification allows areas with similar focal lengths of the solar field to be covered by identical structures. However, for the design of a whole solar field, deviations to the "correct" focal lengths have to be considered since they can lead to losses in solar concentration.

The optical efficiency, that is, the solar concentration, significantly depends on an ideal paraboloidal-shaped reflecting surface. Deformations due to specific action effects, for example, self-weight and wind loads, or initial deviations, for example, due to manufacturing or assembly, cause slope deviations of the surface which are derived from the gradient of the deformations. These slope deviations (*SD*) are widely used to determine the optical quality by means of the root-mean-square (rms) value. For the Stellio heliostat, an *SDrms* value of 1.25 mrad⁵ was verified, which defines the benchmark for the conceptual designs presented here. Since this value was determined at the already assembled and functional heliostat, a separation between *SD* from bending, that is, because of deformations of the bearing structure, and from waviness, that is, due to deformations of the mirror surface, is made. The square root of the squared sum defines the accuracy criteria used here (Equation (2)).

$$SD_{rms} = \sqrt{SD_{rms,bending}^2 + SD_{rms,waviness}^2} \le 1.25 \,\mathrm{mrad}$$
 (2)

Assuming that both components are equally weighted, the limit value for dimensioning the bearing structure is derived to $SD_{rms,bending} = 0.88$ mrad. The second design aspect is the limitation of tensile stresses, so to ensure an uncracked state I.

2.3 | Symmetry reduction

Heliostats possess a relatively low curvature based on high focal lengths. Additionally, heliostats made from concrete are mainly loaded due to self-weights – arising from the concrete structure and mirror elements – and are most stressed in the horizontal position – meaning that they look straight up – with dominant vertical loads. Hence, it is possible to idealize the heliostats for a conceptual design as rotationally symmetric plates which are point-wise supported in the center (Figure 4, top). According to *Markus and Otto*,¹³ the plate can be idealized as a cantilever arm with the radial coordinate *r* and a length set to the heliostat's radius *R* (Figure 4, bottom). The dimensionless coordinate ρ defines the ratio of both (Equation (3)).

$$\rho = r/R \tag{3}$$

The thickness of the plate or cantilever arm, respectively, exhibits a hyperbolical increase in thickness which is defined by the height h_1 at the edge and a shape factor *n* within a power law of ρ (Equation 4).



FIGURE 4 Rotationally symmetric plate with hyperbolical thickness and loads acc. to¹³ (top); partial structure defined by the angle φ and corresponding equivalent statical system of a cantilever arm (bottom)

$$h(\rho) = h_1 \rho^{-n/3} \tag{4}$$

Increasing *n* results in more and more reduced heights (Figure 5, left). For a modular segmentation of the plate, partial structures can be determined defined by the angle φ (in [rad]) (cf. Figure 4). Their (radial) moment of inertia I_r can be derived to:

$$I_{\rm r} = \frac{1}{12} R h_1^3 \rho^{1-n} \varphi \tag{5}$$

As expected, I_r also essentially depends on n. For n = 1, I_r is constant over the length since rigidity losses due to the decreasing height are fully compensated by the increasing circumference of the circular partial structure u_{ϕ} (Equation (6)).

$$\mathbf{u}_{\varphi}(\rho) = \mathbf{R}\rho\varphi \tag{6}$$

In Figure 5 (right) the normalized moments of inertia are shown for the corresponding heights with different shape factors *n*. Each height and moment of inertia is normalized to its value for $\rho = 0.025$ since the height tends analytically to infinity for $\rho = 0$. For a conceptual design, n = 1.5 is chosen since it represents a good compromise between plate thickness, that is, weight, and rigidity.



FIGURE 5 Normalized height h (left) and corresponding normalized moment of inertia Ir (right) for the idealized plate models

TABLE 2 Cross-sectional dimensions of the heliostat designs shown in Figure 8

	Angle	Radial beam		Inner ring		Outer ring		Secondary struts	
Design	φ (°)	Width (cm)	Height (cm)	Width (cm)	Height (cm)	Width (cm)	Height (cm)	Width (cm)	Height (cm)
D30	30	10	27.5-20	10	27.5	10	10	6	10
D45	45	10	32.5-22.5	10	32.5	10	10	8	10
D60	60	10	35-25	10	35	13	13	8	10

Moreover, the applied loads are simplified. They comprise from a constant area load p, representing wind loads and dead loads of reflector elements and secondary concrete struts, a circular line load P_r , depicting the outer ring beam for post-tensioning, and the self-weight g, defined by the thickness of the plate (cf. Figure 4). Post-tensioning forces are not yet considered here. The resulting loads from self-weight G, area load P, and circular line load G_r according to Figure 4 are given by:

$$G = \frac{6}{6-n}R^2\pi g_1 \tag{7}$$

with $g_1 = \gamma_c h_1$

$$P = \pi R^2 p \tag{8}$$

$$G_r = 2\pi R P_r \tag{9}$$

with
$$P_r = A_c \gamma_c$$

Hereby, the area load *p* is assumed to 0.5 kN/m², the area A_c represents the outer ring stiffener's cross section, which is assumed to 0.01 m² (width to height ratio of 0.1 m to 0.1 m, cf. Table 2) and the concrete's bulk density yields to γ_c = 25 kN/m³ (cf. Table 1). As mentioned, the radius is set to *R* = 3 m.

Based on the derivations in¹⁵ the bending moments, which are transferred into stresses, as well as deformations and corresponding deformation gradients, that is, slope deviations, can be obtained. For the form-finding of the concrete structure, the thickness of the plate –

steered by the height h_1 – is adjusted so that the restrictions, that is, slope deviations and tensile stresses, are fulfilled. Thereby, action effects and material resistance parameters are set to characteristic values since the form-finding here serves as a pre-design. The calculation is performed using spreadsheet analyses. The resulting deformations and slope deviations are shown in Figure 6 (left). The corresponding bending stresses for the radial (r) and circumferential direction (φ) fall below the limiting tensile stress of 6.6 MPa (Figure 6, right). Though, the maximum moment m_r results at the support of the idealized cantilever arm, the maximum stress is reached for $\rho \approx 0.2$. This holds true since the height and, therefore, the stiffness is superproportionally increasing compared to the moment. The limit value of the slope deviation SDrms of 0.88 mrad (cf. section 2.2), which results from the course of SD, turns out to be the dominant restriction. The resulting course of the height based on the reduced model is subsequently used to derive stiffness-equivalent modular strut structures as conceptual designs for further analyses.

2.4 | Derivation of stiffness-equivalent beams and partial structures

For the concrete heliostat, the developed plate segments ("piece of cake") have to be transferred into equivalent struts. Based on the thickness of the plate *h*, radial beam elements are derived which exhibit an equal resultant stiffness with respect to φ (cf. Equation (5)). In Figure 7 the plate heights and the corresponding moments of inertia are illustrated for selected angles φ of 30°, 45°, and 60°. Based on



FIGURE 6 Deformation v and slope deviation SD of the equivalent plate model (left) and corresponding stresses σ (right)



FIGURE 7 Thickness of the plate *h* (black) with corresponding stiffness I_r (red) and equivalent height of beams h_{beam} with a width of 10 cm (green) for different angles φ , R = 3 m

these angles, the concrete heliostats will consist of 12, 8, and 6 modules, respectively. The radial beams of these modules are now derived from the equivalent moment of inertia \tilde{I} , whereby the width of the beam w is initially set to 10 cm. The resulting heights are shown in Figure 7 for different module sizes. Additionally, the grayed out supporting area represents the internal ring of the strut structure where the radial beams meet. It possesses an internal radius of 0.25 m.

For the conceptual designs, the beam height is linearized. The strut model is then enhanced incorporating the inner ring for the support, the outer ring for the post-tensioning and secondary struts for stability demands and additional support of the mirror elements. The basic pattern of the struts is oriented to the flux of forces, whereby, next to the surface loads, also the post-tensioning is taken into account. Doing so, the struts are arranged in a way that the loads are transferred from the outer ring, either directly or through the secondary struts, to the main radial beams and finally to the support through the internal ring. The conceptual designs of the heliostats are shown in Figure 8 with their main outer dimensions. To differentiate the modular designs in the following, they are denoted according to the size of φ to D30, D45, and D60.

The designs mainly differ between their patterns of the secondary struts. For D30, only circumferential beams are arranged since prestressing forces are almost directly applied into the radial beams. With increasing partial angles, bending tensile stresses in the outer ring due to post-tensioning become more crucial. Hence, additional radial beams are necessary. For D45, a Y-shaped strut pattern is derived, combining mirror support and load transfer. For D60, with an enlarged circumferential distance of 2 m (for r = 2 m) a triangle-shaped pattern is chosen. The cross-sectional dimensions of all struts are summarized in Table 2.

3 | ANALYSIS OF MODULAR STRUCTURES

3.1 | Numerical modeling

For a detailed analysis, the conceptual designs are transferred into parametric numerical models. They are steered in their single curvatures by the focal length. The numerical models are built up in the Finite Element environment ANSYS 18.0 and consist of spatial 2-noded beam elements with 6 degrees of freedom (3 lateral and 3 rotational) per node. They use the geometrical dimensions according to Table 2. The mirror surface is modeled by 4-noded shell elements with 6 degrees of freedom per node.

The beams represent the concrete structure and possess a linearelastic material behavior since stresses are restricted underneath the HPC's axial tensile strength. The Young's modulus is set to 47.500 MPa. For the mirror panels, an effective Young's modulus of 38.200 MPa is derived from the mirror element "vegaprime" of the company Almeco²¹, which is developed specifically for CSP



FIGURE 8 Conceptual designs of the heliostats with module sizes according to φ of 30° (D30), 45° (D45), and 60° (D60)

applications. It is built up as a composite structure with a top and a bottom layer of 0.5 mm aluminum each and a plastic core. With a total height of 4 mm, it exhibits a stiffness of EI = 2.036 kNcm²/m.

3.2 | Specific loads

3.2.1 | General

For the numerical analysis of the modular structures, all relevant loads are considered close to reality and specified in the following. Next to dead and wind loads, the circumferential post-tensioning is now included.

A differentiation between two situations is made, namely the operation and the survival state. In operation state, the heliostats orientation is variable, whereby only moderate wind speeds up to 10 m/ s might occur. In survival state, the heliostat is fixed in stow position, that is, horizontal mirror panel, where wind pressure coefficients are much smaller compared to the operation state. But, storm events with wind speeds up to 33 m/s are considered here. While in operation state the accuracy demands of solar concentration have to be fulfilled for every position of the collector, in survival state just a non-cracked state has to be ensured. However, a horizontal heliostat position is decisive for both states because of the dominant self-weight. Temperature constraints are of minor importance as they almost solely result in residual stresses and cause negligible deformations.²² Constant temperature differences ΔT_N , for example, over the year, do not distort the structure and temperature gradients ΔT_M are rather low, since the concentrator "blocks" direct radiations.

3.2.2 | Dead loads

Dead loads arise from the self-weight of the concrete structure and the mirror elements. The self-weight of concrete is defined by its bulk density of 25 kN/m^3 . The one of the composite mirror elements corresponds to an area load of 5.5 kg/m^2 that can be converted to an equivalent bulk density of 13.75 kN/m^3 .

3.2.3 | Wind loads

Wind loads mainly depend on the wind flow around the structure. Codified wind load coefficients cover wide ranges of applications and boundary conditions. Insofar, they might overestimate specific load situations. Consequently, DIN EN 1991-1-4²³ permits properly configured wind tunnel experiments to gain coefficients for individual cases. Thus, various wind tunnel tests²⁴ have been performed, most of them for heliostats with rectangular shapes or parabolic dish collectors.^{25–27} Results are mainly force and moment coefficients c_F or coefficient of pressure distributions c_p , respectively. They differ for the spatial position of the heliostats. Load coefficients are used to design the supporting structure.

In this study, the pressure coefficients according to Gong et al.²⁷ are adapted and applied in the decisive horizontal position. Therefore, a conservative approach with a constant pressure distribution is applied. The pressure coefficient is set to $c_p = 0.30$, whereby local suction is disregarded and the resulting wind load is overestimated. Local effects at borders are not considered.

To generate a quasi-static wind load q_{w} , the pressure coefficient is multiplied by the gust pressure q_b that results from the reference wind speed v_{ref} . v_{ref} differs for operation (10 m/s) and survival state (33 m/s).

$$q_w = c_p \cdot q_b \tag{10}$$

with:

$$q_b = 0.5 \rho_{air} v_{ref}^2 \tag{11}$$

Thereby, the air density ρ_{air} is 1.25 kg/m³. In operation state, q_w results to 0.02 kN/m² and 0.20 kN/m² in survival state.

3.2.4 | Post-tensioning

The post-tensioning is achieved using an external monostrand, stressed around the outer ring. The chosen monostrand type BBV Lo1²⁸ exhibits a strength class of St 1570/1770, a diameter d_P of 15.3 mm, and an effective area A_P of 1.4 cm². The resulting post-tensioning force P_0 yields 178.5 kN. Due to the circular deviation of the monostrand, friction losses occur. According to *Rombach*,²⁹ these losses can be determined with respect to the angular displacements Θ to:

$$\Delta \mathsf{P}_{\mu} = \mathsf{P}_0 \cdot \left(1 - e^{-\mu\theta}\right). \tag{12}$$

Hereby, μ describes the friction coefficient of 0.05 for external monostrands.²⁹ Assuming the sum of Θ being 2π , a mean post-tensioning force $P_m = 153$ kN is derived for a one-sided tensioning. Based on P_m , an inward, line-like deviation load u (Equation (13)) arises that holds the modules together and prestresses the radial struts. It results to ≈ 50 kN/m.

$$u = \frac{P_m}{R} \tag{13}$$

3.3 | Numerical analysis of deformations

The developed structures are loaded by the described action effects. The analyses are performed using characteristic values in operation and survival state.

For the accuracy analysis in operation state, deformations are derived. These deformations result from an approach with reduced stiffnesses whereby stability constraints of the struts have been disregarded. Thus, it is a conservative approach. The deformations are illustrated exemplarily in Figure 9 for D45 with a focal length of f = 36 m. Thereby, a group of heliostats near the central tower is defined (cf. Figure 3). Figure 9 shows the deformations caused by dead loads (left), operational wind (center), and the inward deviation forces of post-tensioning. The first two figures illustrate reduced deformations at the supporting struts, increased ones in-between where the softer mirror elements lie. The circumferential deviation forces result in inward deformations that decrease from the outer ring to the center of the circle (Figure 9, right). Deformations due to dead loads rise to the circular edge yielding almost 1 mm. The deformation of posttensioning appears similar but in the opposite direction, as it represents upward bending caused by the eccentricity of posttensioning due to the curvature of the heliostat. Thus, the corners lift up. The deformations based on wind effects mainly cause distortions of the mirror elements. The concrete struts remain almost undeformed. The deformations are much smaller compared to dead loads.

The deformations are superimposed and the resulting slope deviations are derived. This is done in Cartesian x- and y-coordinates, that is, in the plane of the collector. In contrast to the predesign, where only the bearing structure was analyzed, now also the mirror surface is taken into account. Hence, an overall slope deviation of *SDrms* \leq 1.25 mrad has to be fulfilled.

In Figure 10, superimposed deformations (left) and resulting slope deviations (center and right) are shown. Thereby, the root mean square values of the *SD* of *SDx,rms* = *SDy,rms* = 0.84 mrad are achieved which result in an overall accuracy of *SDrms* = 1.19 mrad. As mentioned, the post-tensioning seems to diminish or compensate deformations from self-weight. For low curvatures, that is, heliostats with a higher focal length, this effect is smaller. To check this hypothesis, an increased focal length of 136 m (cf. Figure 3) is also tested and plotted in Figure 10 (bottom). But, slope deviations of *SDx, rms* = *SDy,rms* = 0.74 mrad are determined to yield *SDrms* = 1.07 mrad and thus a more accurate surface. Consequently, small values of *f* govern the design and are assumed in the following. It should be noted, that lowering the post-tensioning force to decrease the



FIGURE 9 Deformations of the heliostat structure with a partial angle of 45° and a focal length of 36 m due to dead loads (left), wind load (centre), and post-tensioning (right)



FIGURE 10 Superimposed deformations (left) and resulting slope deviations SDx (center) and SDy (right) for a focal length of f = 36 m (top) and f = 138 m (bottom), and a partial angle of 45° (D45)

-1 0 1 coord. x [m]

-3

-3 -2

2 3 -2

2 3 -3∟ -3

-2 -1 0



FIGURE 11 Superimposed deformations (left) and resulting slope deviations SDx (center) and SDy (right) for D30 (top) and D60 (bottom) and a focal length of f = 36 m

distortion is not an option, since the radial beams have to be fully compressed not only in operational but also in survival state. Thereby robustness against varying load situation due to dead and wind loads with respect to the heliostat's position is ensured.

100

-3∟ -3

-2 -1 0

> Analyses of D30 and D60 reveal that both exhibit a higher stiffness than D45. Additionally, the posttensioning seems to almost equalize the edge deformations when superimposed with the other action effects (Figure 11, left). Thereby, SD mainly occur due to the

-2

2 3

TABLE 3 Characteristics of the concrete heliostats with respect to their partial structure's size

Design	Angle ϕ (°)	No. of modules	Slope deviation SDrms (mrad)	Volume V (m ³)	Total weight m (t)	Weight per module (t)
D30	30	12	0.78	1.10	2.74	0.228
D45	45	8	1.19	1.00	2.50	0.313
D60	60	6	0.94	1.12	2.80	0.466



FIGURE 12 Influence of the module's geometrical uncertainty (left) on the circumference of the heliostat dependent on the number of modules (right)

waviness of the mirror elements. These deviations are smaller in case of D30 since more radial beams and consequently smaller support distances of the mirror elements exist. This results in *SDrms* = 0.78 mrad for D30 and *SDrms* = 0.94 mrad for D60.

In the survival state, the tensile strength of concrete is not exceeded for all models. The radial beams, as well as the outer and secondary beams, stay fully compressed. This holds true for small focal lengths. For large ones, the positive effect of prestressing is reduced and bending tensile stresses occur within radial beams due to self-weight and wind loads. For robustness demands, additional reinforcements are recommended. This applies to all struts.

Two parameters of variations should be discussed. First, an increase of prestressing. A monostrand with fixed cross section is used here that could only be doubled, so applying two strands. Due to cost reasons, the design is restricted to one strand. Second, a regular HPC could be used as a much cheaper material that easily withstands the occurring compressive stresses. However, it would require a larger concrete cover due to durability reasons. The cross sections of all struts would pronouncedly increase. Moreover, it fails in providing sufficient tensile strength capacities. Consequently, the chosen compound turns out to be the most effective for this design case.

3.4 | Discussion of designs

The derived designs differ in accuracy, module sizes and, as a consequence, the number of modules, and weight. The main characteristics are summarized in Table 3. For every design, the accuracy demands are met. However, the highest accuracy accounts for D30, a minimum accuracy results from D45. Thereby, *SD* are mainly dependent on the waviness of the mirror elements and, hence, their stiffness as well as the distance between the concrete struts. Thus, the accuracy could easily be improved by stiffer mirror elements, which then entail increasing costs. The maximum weight of the heliostat structure results from D60, whichconsequently possesses the maximum weight for the segmental modules. D30 exhibits the minimum weight of the modules, but almost an equal weight as D60 for the whole structure. To cut material costs, D45 is preferred, since it reduces >10% of the mass compared to D60. For further reductions elaborated methods like topology optimizations are recommended.^{30,31} They help to identify more effective material distributions.

Due to the high amount of identical modules, serial production seems to be appropriate, especially when considering a whole solar field. For assembly, precise joints have to be ensured since geometrical uncertainties from the production process would accumulate for the whole heliostat. Figure 12 illustrates this influence of geometrical uncertainties per joint Δu_i defined by a normal distribution with an exemplarily mean deviation of $\mu_0 = 2$ mm and a standard deviation $\sigma_0 = 1$ mm (left) and the resulting deviation of the heliostat's circumference Δu (right). Δu is depicted by a mean value (solid line) and max/min values (dotted lines) which represent the scattering range – generated by a Latin-Hypercube Sampling³² – of the global uncertainty. Both, mean value and scattering range, are linearly increasing with respect to the number of modules. This means that with increasing modules the expectable uncertainty of the heliostat also increases and leads to gaps in-between the modules.

Ernst & Sohn 101

Ernst & Sohn

102

the heliostat might be prohibited. Conversely, the requirements for a precise production increase with the number of modules to ensure a force-fit coupling. Hence, automated flow production with integrated quality control is recommended.³³

4 | CONCLUSIONS

Developments of heliostats mainly aim for cost reductions since they account for around 40% of the CSP plant costs. Doing so, modular designs of heliostats made from HPC are derived. The main findings are:

- Methods of system reduction help to identify suitable designs for the axially symmetric structures. Appropriate modules subdivide the circular dish into segments of 30°, 45°, or 60° that appear like "pieces of a cake."
- Concrete heliostats can be idealized by equivalent plate systems. The plates can be transferred into strut-like structures preserving a mean equivalent stiffness. For dimensioning, accuracy demands dominate material restrictions.
- Numerical analyses reveal that deformations due to self-weight and post-tensioning almost equalize each other. Deformations which cause significant slope deviations mainly result from the waviness of the mirror elements.
- The modular structures distinguish between their number of modules, weight, and stiffness. The one with a module size defined by φ = 30° exhibits the highest stiffness and the module defined by φ = 45° the lowest weight. Thus, this last type is preferred.
- The heliostats should be fabricated in serial productions. However, increasing numbers of modules let inaccuracies superimpose that must be controlled by quality assurance.

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