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Light concrete shells for parabolic trough collectors – Conceptual design, prototype and proof of accuracy

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Abstract

Up to now modules of parabolic trough collectors are usually made from steel frames carrying curved mirror elements. With these, the crucial disadvantage is the separation between supporting structure and reflecting surface. Here, the independent parts are merged to a very thin and light-weight but solid concrete shell having a highly precise inner surface that serves as substrate for mirror elements. Since concrete is originally very brittle and weak in tension, a special high-strength concrete with remarkable tensile strength is developed.

Based on numerical analyses employing linear elastic material behaviour and limiting stresses below the tensile strength, two alternative module candidates have been designed with geometries close to already existent modules. Their design accounts for operation states by means of analytically and experimentally derived actions and constraints as well as time-dependent material effects. A first prototype on novel concrete supports demonstrates general feasibility. Highly accurate surfaces of the concrete shell, having a few centimetres of thickness only, prove structural stiffness and full optical efficiency in tests employing digital close range photogrammetry and analytically derived precision rates based on the surface slope error.

Keywords: Parabolic trough; Slope error; Wind loads; High-strength concrete; Shell structures; Photogrammetry

1. Introduction

Parabolic trough collectors are the most mature technology for solar thermal power plants currently available. Actually, around 40 plants with a total installed power of more than 2 GW are operational worldwide, mainly in Spain and the US. State-of-the-art are steel or aluminium structures carrying curved glass mirrors. Collectors of up to 150 m total length are built up from modules with lengths of 12 m and an aperture width of about 5.80 m, e.g. the first parabolic trough solar power plants in Europe Andasol 1–3 (Solar Millennium, 2008). Current developments aim to reduce costs by economies of scale, increasing the aperture to 19 m by 6.77 m in case of the HelioTroughs (Riffelmann et al., 2009; Köttler et al., 2012) or to 24 m by 7.50 m in case of Ultimate Troughs (Riffelmann et al., 2013; Schweitzer et al., 2014) per module. An overview of

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Nomenclature

A	projected area (m^2)
C	concentration ratio
CSR	circumsolar ratio (%)
$\mathbf{C}$	correlation matrix
$c_{p,net}$	coefficients of surface pressure
d	receiver diameter (mm)
E_c	concrete Young's modulus (N/mm^2)
f	focal distance (m)
f_c	concrete compression strength (N/mm^2)
f_{ct}	concrete tensile strength (N/mm^2)
f_{pt}	acceptance function
$\boldsymbol{\Delta H}$	random field fluctuation (mm)
l	collector length (m)
m	mass (t)
n_l	number of nodes in longitudinal direction
n_{sp}	number of nodes of the c-spline approximation
q	wind pressure (kN/m^2)
t	time
t_0	shell thickness at centre (cm)
t_1	shell thickness at the edges (cm)
ΔT_M	linear variable temperature distribution (°C)
ΔT_N	constant temperature difference (°C)
W	Wind load (kN/m^2)
w	aperture width (m)
V	volume (m^3)
v	wind speed (m/s)
$x_{i,j}$	sampling point coordinates
$z_{t,dev}$	trend estimation of vertical deviations (mm)

Greek

ε_c	concrete strains (mm/m)
ε_{cr}	creep strains (mm/m)
ε_{cs}	shrinkage strain (mm/m)
$\bar{\varepsilon}_{el,24h}$	mean elastic strains during a solar day
η	collector efficiency
θ	slope error (mrad)
$\boldsymbol{\Lambda}$	eigenvalues
μ	mean value of the slope error (mrad)
$\underline{\xi}_{ij}$	individual form deviations
$\bar{\xi}_j$	mean but trend-free form deviation
ρ	air density, 1.25 (kg/m^3)
ρ_c	density of concrete (kg/m^3)
σ	standard deviation of the slope error (mrad)
σ_{ct}	concrete tensile stress (N/mm^2)
σ_H^2	variance of a random field
Φ	pitch angle (°)
$\boldsymbol{\phi}$	eigenvector
$\varphi(t, t')$	creep function
φ_r	rim angle (°)

the evolution of parabolic troughs and their applications is given in Fernández-García et al. (2010). However, significant further cost reductions can only be expected from changing to different structural concepts and cheaper construction materials. Precast concrete components can be produced in high-precision and at low cost. Moreover, since the materials and technology are commonly available worldwide, the use of concrete as structural material for parabolic trough collectors would also create the benefit of increased local added value. However, the quality of the local raw material supply has to be verified to ensure a successful localisation. The first known concrete solar collector has been presented by the Swiss company "Airlight". This collector is assembled from precast concrete elements carrying a proprietary multi-arc pneumatic mirror system (Pedretti, 2012; Schweitzer et al., 2014). By contrast, the approach outlined in the remainder aims to combine the structural benefits of a solid but light-weight high-strength concrete shell with a high-precision inner surface, which should serve as substrate for a concentrating mirror.

The investigations have been performed in cooperation of the Ruhr-University Bochum, responsible for numerical analyses and derivations of specific action effects as well as loading scenarios, the Technical University of Kaiserslautern realizing the prototype structure, the German Aerospace Center (DLR) supporting the specification and optical qualification of the prototype, and Solarlite CSP Technology GmbH, an experienced industrial partner with respect to innovative collectors.

Table 1
Dimensions and characteristics of the parabolic trough models.

Description	Dimensions	
	Model "EuroTrough"	IST PT-1/own prototype
Parabola length l (m)	12.00	6.10/3.20
Parabola aperture width w (m)	5.77	2.205
Focal distance f (m)	1.71	0.78
Rim angle φ_r (°)	80	70
Receiver diameter d (mm)	70	51
Concentration ratio $C = w/d$ (–)	82	43

2. Conceptual design and numerical modelling

The conceptual design of parabolic troughs made from high-strength concrete comprises both, numerical analyses and experimental testing. In general it is leaned on two existent basic designs of collectors, whose main characteristics are summarized in Table 1. Both mainly differ in size, geometry and bearing conditions. While the first one is inspired by the widely commercially used "EuroTrough"