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Energy Procedia 00 (2015) 000–000
Energy Procedia
www.elsevier.com/locate/procedia

The 7th International Conference on Applied Energy – ICAE2015

# Evaluation and assessment of gravity load on mirror shape of parabolic trough solar collectors

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**Abstract**

In order to achieve high optical collector and therefore high solar field efficiencies parabolic trough concentrators in concentrating solar power plants need to maintain their parabolic shape during operation. Additional to shape deviation already induced by the manufacturing process, deformation due to gravity load is an inevitable factor influencing shape accuracy in all types of parabolic trough collectors.

This paper characterizes and quantifies the effect of gravity load on mirror shape and resulting slope and focus deviation values. One inner and one outer ideally parabolic shaped mirror of RP3 geometry mounted onto different support structures are evaluated in finite element analyses for all collector angles relevant for operation. The different support structures include two idealized support structures (ideal and elastic case) and one structure including relevant parts of EuroTrough type collectors (cantilever case).

Constructional design and stiffness of the support structure significantly determine characteristic and magnitude of deformation. If compared to non-deformed shape, resulting rms values are as high as $SDx = 1.7$ mrad and $FDx = 6.3$ mm (inner mirror, elastic case) and $SDx = 1.1$ mrad and $FDx = 5.6$ mm (outer mirror, cantilever case). Depending on the type of support structure, minimum and maximum values occur at different collector angles. If compared to 0° (zenith) collector angle, resulting rms slope and focus deviation values are on average smaller than if compared to non-deformed mirror shape. This implies optimizing mirror shape for 0° (zenith) collector angle. However, it has to be considered that support structures for shape accuracy assessment in laboratory as well as support structures used in collector might differ significantly in design and stiffness, thus making it difficult to find one optimum shape for all types of mirror and collector.



*Keywords*: parabolic trough; mirror shape; shape accuracy; deformation; finite element modeling;

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## 1. Introduction

Concentrator mirrors in concentrating solar power plants (CSP) require good shape of the reflector panels during operation while the concentrator is continuously tracking the sun position. Deviations from the ideal shape are on the one hand induced by the mirror manufacturing process and on the other hand by inevitable factors in operation such as deformation due to dead load, inaccurate mounting of mirrors to a possibly imperfect collector structure or wind loads. The mirror shape of any kind of concentrator type (parabolic trough, linear Fresnel, heliostat, or dish) is measured in laboratory, in the production line, or in the field by well-established measurement methods such as Video Scanning Hartmann Optical Test (VSHOT) [1], visual inspection systems [2, 3], and the widely spread fringe reflection or deflectometry techniques [4-6]. For studying the effect of loads and mounting forces it is convenient to employ finite element analyses techniques [7]. The modeling approach allows determining the impact of individual influence factors on shape deviation and resulting parameters, as well as analysis of the impact of a combination of two or more factors.

Christian and Ho [8] performed a finite element deformation analysis for a LS-2 parabolic trough collector in two representative positions, zenith collector angle and collector facing horizon. Resulting absolute slope deviation values were as high as 2 mrad for mirrors exposed to gravity load and as high as 3 mrad for a change from one collector angle to the other.

Previous analyses for parabolic trough solar collectors employing RP3 mirror geometry focused on determination of gravity-induced deformation and resulting slope deviation in three selected collector angles and one typical laboratory measurement position for two idealized collector model cases (an ideal case with ideally rigid collector support structure and an elastic case with ideally rigid structure using the elastic connections employed in EuroTrough type collectors to attach the mirrors). The main findings include that slope deviation compared to ideal shape and compared to zenith collector angle are in the magnitude of shape quality itself and that the support structure determines deformation characteristic and magnitude of displacement and resulting slope deviation. For all evaluated angles deformation and thus slope deviation is more pronounced for the elastic case [9].

This paper extends the analyses on parabolic trough solar collectors to the whole angular range in operation, introduces a third model case which includes relevant parts of a EuroTrough type collector support structure, and assesses the impact of gravity-induced deformation in terms of slope and focus deviation parameters. In order to characterize and quantify the effect of gravity load on mirror shape, slope and focus deviation, the deformed mirror in each evaluated angle is compared to the non-deformed mirror shape, and to the shape in zenith collector angle. The purpose of the studies is to understand the effects of supporting geometry, mounting elements and panel properties on the collector performance and possibly derive improved specifications.

## 2. Methodology

### *2.1. Definitions and geometry*

In EuroTrough type concentrators or similar designs with RP3 mirror geometry the parabolic collector shape of 5776 mm width is formed by two inner (1700 x 1641 mm) and two outer mirror panels (1700 x 1501 mm) as reflectors of a cylinder-parabolic collector. The receiver tube is located at a distance of 1710 mm (focal length) from the vertex. The mirror panels are bent and coated 4 mm float glass sheets with four ceramic pads each glued to the mirror back side for mounting to the metallic collector support structure.

By definition [10], the collector coordinate system's origin is located in the parabola vertex. The *y*-axis is oriented parallel to the parabola symmetry axis, pointing in northern direction. The *z*-axis points from the parabola vertex towards the focal line. The *x*-axis corresponds to mirror curvature direction and is oriented in order to have a right-handed coordinate system.

### 2.2. Parameters for the assessment of mirror shape accuracy

In concentrating solar power applications mirror shape accuracy is evaluated in terms of surface slope deviation which is defined as the angle between actual and ideal surface normal vector. An outward rotation of the deformed surface normal vector (pointing to the outer edges of the parabolic trough) is defined as positive slope deviation, an inward rotation (pointing to the center of the trough) as negative slope deviation. A statistical parameter characterizing the shape accuracy of the whole mirror surface is the root mean square (rms) value of local slope deviations *SDx*:

$$SDx = \sqrt{\sum_{i,j=1}^{n}\left(sdx_{ij}^{2} \cdot \frac{a_{ij}}{A_{\mathrm{tot}}}\right)} \qquad (1)$$

with local slope deviation values $sdx_{ij}$, the according surface element areas $a_{ij}$ projected into the aperture plane and the total aperture area $A_{\mathrm{tot}}$.

The maximum allowable value of slope deviation depends on the distance of the reflecting surface element to the focal line and the geometry of the receiver. The deviation of the reflected light beam from the ideal focal line, so called local focus deviation, was introduced as a further parameter characterizing mirror shape accuracy [11]. It is derived from local slope deviation and the distance *d* of the according reflecting surface element to the ideal focal line, e.g. in *x*-direction:

$$fdx_{ij} = \left(2 \cdot sdx_{ij}\right) \cdot d \qquad (2)$$

The factor 2 results from the law of reflection. According to equation (1) a root mean square focus deviation *FDx* can be calculated based on local values.

Based on measured shape accuracy data Lüpfert et al. [11] show that the rms focus deviation parameter *FDx* is closely related to the intercept factor.

### 2.3. Finite element models and analyses

For reasons of symmetry, each model prepared in ANSYS Workbench includes only one half of a mirror column, i.e. one inner and one outer ideally parabolic shaped RP3 mirror on the different support structures explained in the following. Results for the other half of the mirror column may then be obtained by mirroring the presented results along 0° collector angle (zenith). Three different model cases are prepared in ANSYS workbench: an *ideal case*, an *elastic case* and a *cantilever case*.

In the *ideal model case* the mirrors are mounted onto an ideally rigid collector support structure. Fixed boundary conditions that neither allow displacements nor rotations at the mounting pad rear sides are applied.

The *elastic model case* includes the brackets employed in EuroTrough collectors to mount the mirrors onto the collector structure. Fixed boundary conditions are applied where the brackets are attached to the structure. According to their shape the brackets are referred to as “L” and “Z” brackets.

The *cantilever model case* is based on the elastic case and includes additionally the cantilever arms used in EuroTrough collectors. Fixed boundary conditions are applied where the cantilever arms are attached to the torque-box.

The geometry of the different models is simplified where no effect on deformation behavior is assumed: reflective and protective mirror coatings are neglected so that the mirrors consist of 4 mm float glass only; small parts like screws, screw nuts, etc. are not included; all parts are fixed permanently.

The finite element models utilize solid shell elements for discretization of reflector mirrors. All further parts (pads, adhesive, brackets, and further collector structure parts) are discretized using solid elements. Further details of the ideal and elastic finite element model are stated in [12].

Static structural analyses are run for all model cases, changing the gravity vector's orientation in 15° steps from eastern horizon collector angle (- 90°) to western horizon collector angle (+ 90°). The determined displacement data serve as input data for a MATLAB algorithm to calculate resulting local and rms slope and focus deviation values as figure of merit. The displacement data is used in a further evaluation step to determine the change in shape, slope and focus deviation compared to zenith collector position.

## 3. Results

### *3.1. Shape, slope and focus deviation compared to ideal mirror shape*

Deviation from ideal shape due to gravity load for RP3 mirrors mounted onto the three introduced collector support structures is shown in Table 1 and Table 2. Deviation characteristic and magnitude of displacement strongly depend on constructional design and stiffness of support structure: the more rigid the support structure, the smaller are shape deviation and resulting local slope deviation values (compare ideal case). In particular, the “Z”-shaped brackets in the elastic and cantilever case allow an opposite deflection of the inner mirror outer edge and of the outer mirror inner edge in zenith and 90° collector angle if compared to the ideal case. As shown in the according deformation graphic in Table 2, the support structure of the cantilever case allows additionally a stronger deflection of the outer mirror towards the collector outer edge compared to the elastic case. This divergent effect starts to be noticeable for collector angles beyond ± 30° from zenith (compare Figure 1).

As shown in Figure 1, for the ideal case, largest slope deviation values occur when mirror mounting pads are approximately horizontally aligned i.e. – 15° for inner mirrors and – 30° for outer mirrors. On the contrary, smallest values are determined for collector angles with approximately vertically aligned mounting pads i.e. 75° for inner mirrors and 60° for outer mirrors (Table 3). In the elastic and cantilever case, maximum and minimum slope deviation values occur where the support structure allows maximum and minimum deformation, respectively.

Due to the smaller distance between mounting pads in curved ($x$) mirror direction rms slope deviation values are on average smaller for outer mirrors than for inner mirrors, especially in the elastic and the cantilever case (Figure 1). However, in terms of rms focus deviation the values are in the same order of magnitude due to the larger distance of the outer mirror to the focal line.

Table 1: Deformation and resulting slope deviation in zenith (0°) collector angle for ideally shaped RP3 mirrors when mounted onto different support structures and compared to non-deformed shape. Color scale of deformation graphics in mm, deformation scaling factor: 1000; Color scale of slope deviation in mrad.

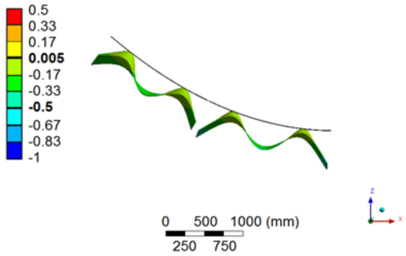
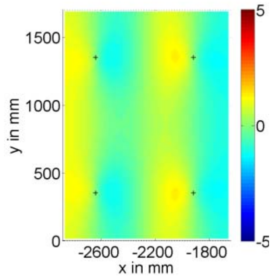
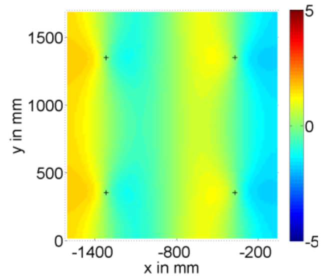
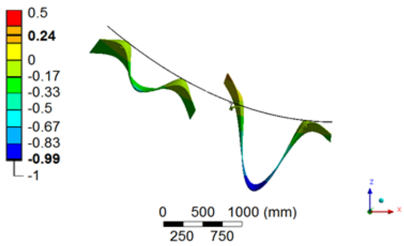
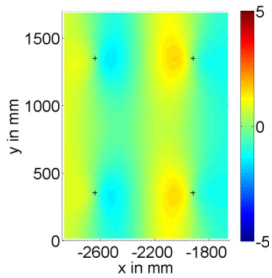
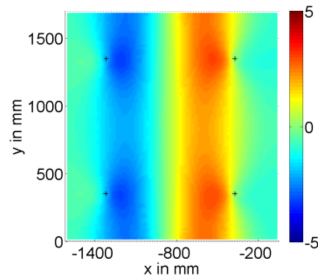
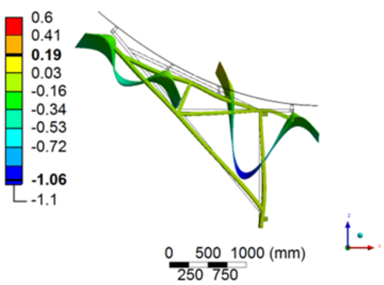
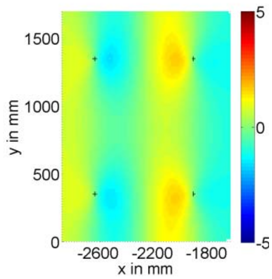
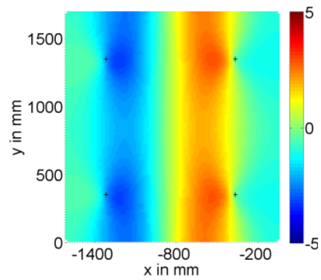
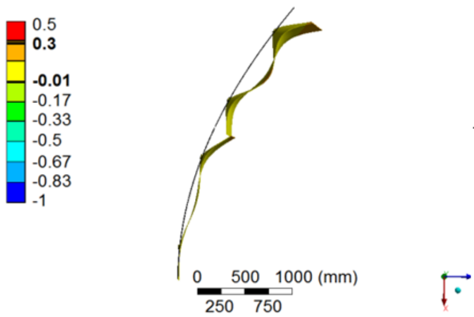
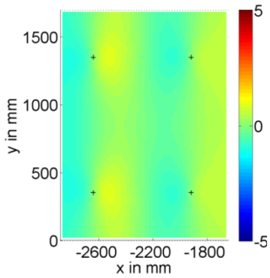
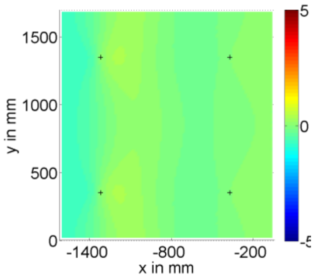
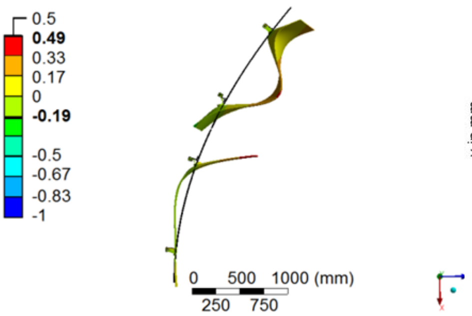
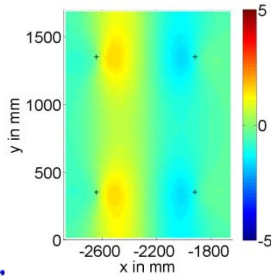
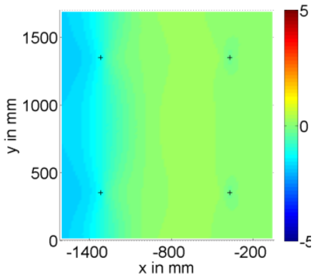
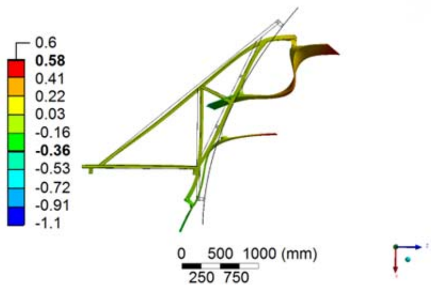
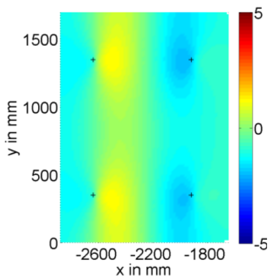
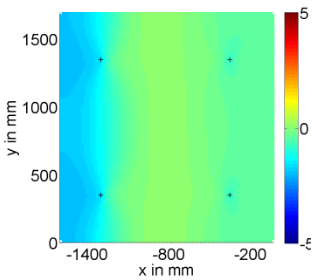
| | Deformation in zenith collector angle | Slope deviation of RP3 outer mirror | Slope deviation of RP3 inner mirror |
|---|---|---|---|
| Ideal case |   |   $SDx$ = 0.76 mrad |   $SDx$ = 0.96 mrad |
| Elastic case |   |   $SDx$ = 0.78 mrad |   $SDx$ = 1.61 mrad |
| Canti-lever case |   |   $SDx$ = 0.8 mrad |   $SDx$ = 1.60 mrad |

Table 2: Deformation and resulting slope deviation in 90° collector angle for ideally shaped RP3 mirrors when mounted onto different support structures and compared to shape in zenith (0°) collector angle. Color scale of deformation graphics in mm, deformation scaling factor: 1000; Color scale of slope deviation in mrad.

| | Deformation in 90° collector angle | Slope deviation of RP3 outer mirror | Slope deviation of RP3 inner mirror |
|---|---|---|---|
| Ideal case |  |  *SDx* = 0.51 mrad |  *SDx* = 0.29 mrad |
| Elastic case |  |  *SDx* = 0.79 mrad |  *SDx* = 0.74 mrad |
| Canti-lever case |  |  *SDx* = 1.0 mrad |  *SDx* = 0.85 mrad |

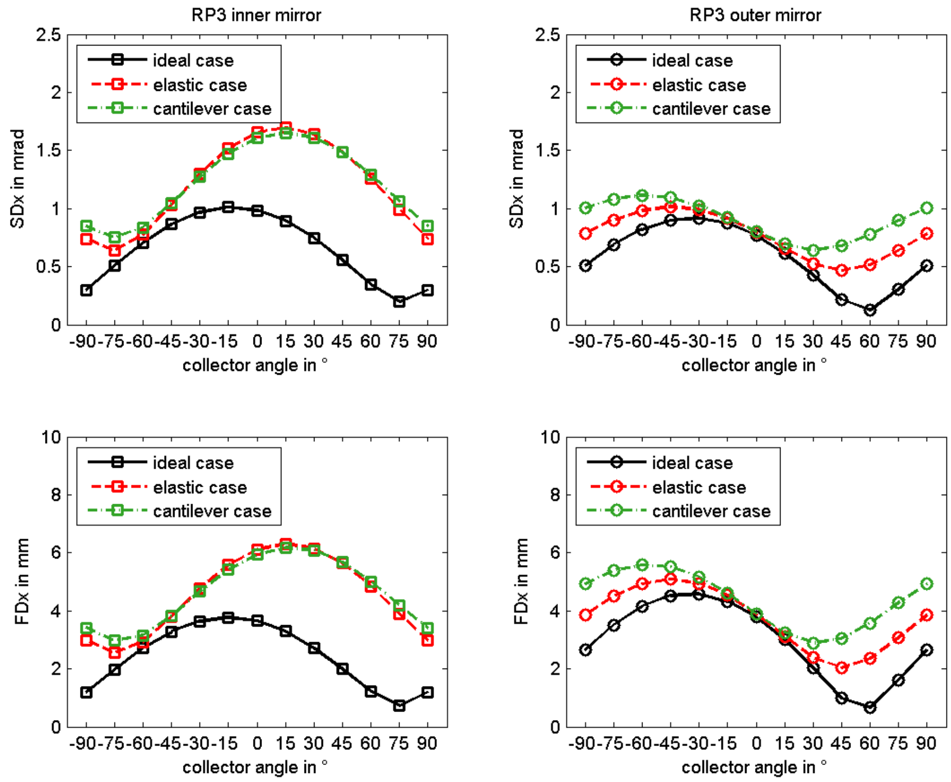



Figure 1: Rms slope and focus deviation for RP3 inner (left) and RP3 outer mirror (right) mounted onto different model support structures and compared to non-deformed mirror shape

Table 3: Minimum and maximum values of rms slope and focus deviation for RP3 mirrors mounted onto different model support structures and compared to ideal mirror shape

| Mirror type | Min | | | Max | | |
|---|---|---|---|---|---|---|
| | Angle in ° | *SDx* in mrad | *FDx* in mm | Angle in ° | *SDx* in mrad | *FDx* in mm |
| Inner (ideal case) | 75 | 0.20 | 0.72 | -15 | 1.01 | 3.77 |
| Inner (elastic case) | -75 | 0.64 | 2.55 | 15 | 1.70 | 6.31 |
| Inner (cantilever case) | -75 | 0.75 | 2.97 | 15 | 1.65 | 6.17 |
| Outer (ideal case) | 60 | 0.12 | 0.65 | -30 | 0.92 | 4.58 |
| Outer (elastic case) | 45 | 0.47 | 2.04 | -45 | 1.01 | 5.09 |
| Outer (cantilever case) | 30 | 0.64 | 2.89 | -60 | 1.11 | 5.58 |

### *3.2. Slope and focus deviation compared to zenith collector angle*

Rms slope and resulting rms focus deviation values for mirrors mounted onto the different examined support structures if compared to zenith collector angle are presented in Figure 2. As expected, slope and focus deviation values increase with increasing collector angle. This effect is even more pronounced for elastic and cantilever case than for the ideal case.

If, for the purpose of a rough estimation, rms slope and focus deviation values are averaged over the range of relevant working positions (-80° - +80°), these averaged rms slope and focus deviation values show less deviation from the zenith case than compared to ideal shape. Graphically these values correspond to the areas below the curves in Figure 1 and Figure 2.

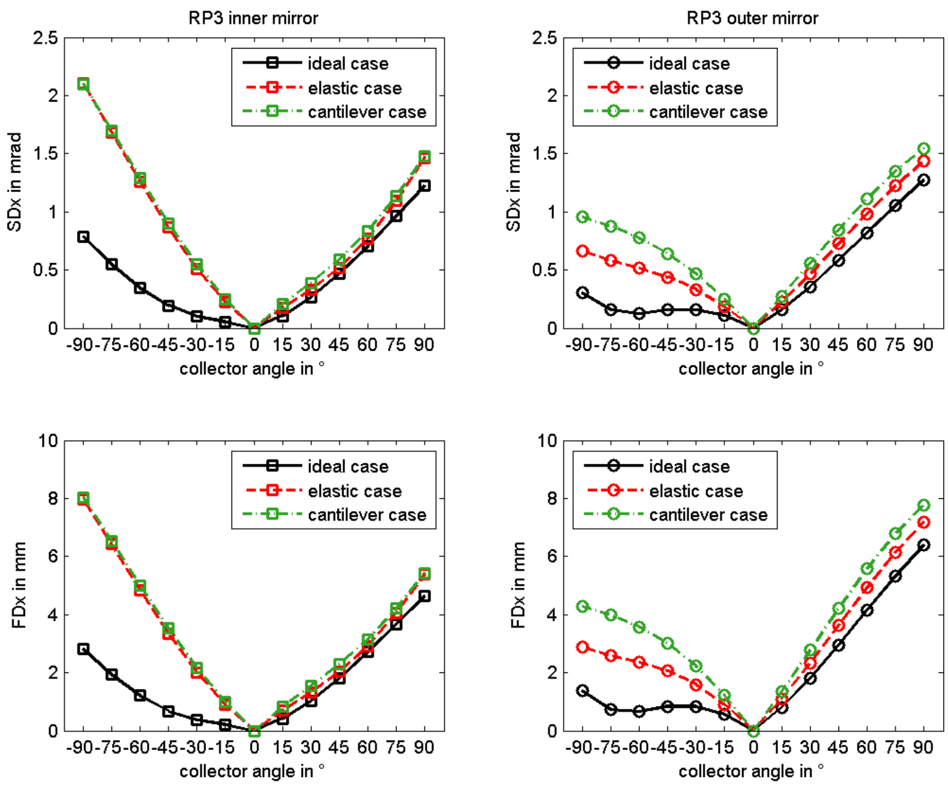



Figure 2: Rms slope and focus deviation for RP3 inner (left) and RP3 outer mirror (right) mounted onto different model support structures and compared to shape in zenith (0°) collector angle

## 4. Discussion

The presented results confirm what was found for selected collector angles in previous work [9]: constructional design and stiffness of the collector support structure significantly determine characteristic and magnitude of deformation due to gravity. If further parts of a EuroTrough type collector structure are included into the model, additional deformation is observed especially for the outer mirror. Determined slope and focus deviation values are in the magnitude of shape quality that is reached by state of the art mirror panels (≤ 2 mrad and ≤ 7 mm, respectively).

For all examined cases the larger distance of mounting pads for RP3 inner mirrors leads on average to higher displacements and thus slope deviation values than for outer mirrors. However, in terms of focus deviation the effect of gravity load has approximately the same magnitude for both mirror types. Consequently, RP3 inner as well as outer mirrors have to be considered for evaluation of optical collector quality. The magnitude of determined focus deviation values indicates that gravity-induced deformation may have a significant impact. In real collector application several further error sources, such as manufactured shape quality itself, mounting inaccuracies, sun shape, etc., contribute to the effect of reflected solar radiation missing the absorber tube (intercept factor).

The analyses of deformation in all collector angles allows an overview on expected deviation values for the examined model cases and clearly indicates the angles with minimum and maximum deformation. For an ideally rigid support structure a maximum mirror deformation occurs where the mirror is oriented with approximately horizontally aligned mounting pads. For the other cases the maximum shifts to different positions where maximum deformation is allowed. This implies the approach of modifying mirror shape in a way that gravity-induced deformation is compensated, in particular in the position with maximum deformation. For example in the ideal case, RP3 inner mirrors could be optimized for a position close to zenith collector position. As the comparison to shape in zenith angle points out, slope and focus deviation values would thus be on average smaller than if compared to ideal non-deformed shape. However, it has to be considered that support structures used for shape accuracy assessment in laboratory likely differ from the ones presented here.

## 5. Conclusion and outlook

Finite element modeling and data post processing on RP3 mirror panels mounted onto three types of support structure with different constructional design and stiffness are employed to characterize and quantify the effect of gravity load on mirror shape, slope and focus deviation for all collector operating angles.

The results demonstrate that the less rigid the support structure, the higher is the impact on magnitude and characteristic of gravity-induced deformation. If compared to non-deformed shape, calculated values of slope and focus deviation are in all cases in the range of shape quality accomplished by state of the art parabolic trough mirror panels. Even though on average smaller slope deviation values are determined for RP3 outer mirrors, the resulting focus deviation values are, due to the larger distance to the collector focal line, of the same magnitude as for inner mirrors. The analyses of deformation over the whole collector angular range reveal different minimum and maximum values for inner and for outer mirrors, additionally depending on the type of support structure: Maximum determined values are $SDx = 1.7$ mrad and $FDx = 6.3$ mm for inner mirrors in -75° collector angle (elastic case: ideally rigid structure using the elastic connections to attach the mirrors), and $SDx = 1.1$ mrad and $FDx = 5.6$ mm for outer mirrors in -60° collector angle (cantilever case: support structure including additionally the cantilever arms used in EuroTrough collectors).

If compared to 0° (zenith) collector angle, resulting rms slope and focus deviation values are on average smaller than if compared to non-deformed mirror shape implying that optimizing mirror shape for 0° (zenith) collector angle can be beneficial. This approach, however, has to consider the different designs and stiffnesses of support structures employed in collector and laboratory.

Finite element analyses have proven to be a helpful tool to assess the impact of gravity on collector deformation and resulting slope and focus deviation. In order to be able to reliably predict achieved mirror shape accuracy in an operating collector a next step is to validate the deformation results of the cantilever model case by using actual shape measurement data.

## Acknowledgements

The financial support for part of this work by FLABEG FE GmbH in the framework of a cooperation project, as well as by the German Federal Ministry for the Environment, is gratefully acknowledged.

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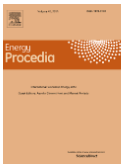


## Biography

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