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Structural analysis of mirror bent strips and connection elements for heliostat with drive rims

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ABSTRACT
Heliostat is considered the component with the greatest impact on the costs of a CSP plant with a central tower and the use of the appropriate heliostat can generate reductions of up to 40% in energy losses. In this sense, it is necessary to nationalize the structural and optical components of the same as a cost mitigation measure, with solutions that favor the introduction of technology in the Brazilian agroindustry. In addition, there is a need for studies so that CSP technology adapts to tropical latitudes, which require shorter focal length and, therefore, the use of narrower heliostat fields than at latitudes such as Europe and the United States, places where CSP technology is already commercially established. The solution proposed in this study requires the use of a mirror with a curved surface in order to achieve the required concentration using a low number of heliostats, reduce spill losses and increase the amount of energy absorbed and, consequently, the performance of the solar plant. A reflective surface configuration was proposed, consisting of six horizontal mirror strips that were designed using the Autodesk Inventor program and submitted to structural analysis by the Finite Element Method (FEM) with the ANSYS Workbench program. In the simulations, a wind load that can occur in São Paulo was applied and the results of stress and deformation in the mirrors were analyzed. In order to optimize the use of material in the mirror, two thicknesses were proposed: 4 and 7 mm. The 4 mm thick mirror can become a solution, although it has been shown to be susceptible to tension caused by the wind, near the central connecting elements positioned next to the support of the drive system. In addition, an option to connect the mirrors to the frame via an L-shaped angle bracket is presented as a solution.

Keywords: Concentrated Solar Energy, Heliostat, Mirror Strip.

1 INTRODUCTION

Concentrated Solar Energy, or Heliothermic Energy, is ready to take an important role in Brazilian agribusiness. Concentrated solar power systems produce electrical energy by converting solar energy into high-temperature heat using various mirrored surface configurations. These systems focus direct solar radiation through optical devices to a receiver, transforming the radiation into high-temperature heat, suitable to produce steam.

In a country like Brazil, which has a large territorial extension, with a high incidence of solar radiation, it becomes possible to develop technologies capable of transforming solar energy into thermal and electrical energy. Although the availability of solar radiation is usable, the interest in the use of CSP technologies in the generation of electricity is recent. Such interest has been motivated by different reasons, among which are national and international policies to encourage the use of renewable and clean energy sources in the face of the fear of climate change and the current energy crisis that the country is facing.

CSP plants with central tower system consist of a field of heliostats (mirror or set of mirrors that can be directed during the day to reflect sunlight on a stationary receiver) and move independently and concentrate solar radiation on top of the tower (EPE, 2012).

In this sense, it is necessary to nationalize the structural and optical components of heliostats, as a cost mitigation measure, with solutions that favor the introduction of the technology in the Brazilian agribusiness market. In addition, there is a need to develop studies to adapt CSP technology to tropical latitudes.

The reduction of the levelized cost of generating electricity generated by CSP plants, obtained with reductions in their cost of capital, increased plant efficiency and gains with economies of scale, can reach, in a time horizon similar to the long-term Brazilian energy planning horizon, 40 to 50% of the levelized cost of energy of the first large-scale CSP plants installed in the world (IRENA, 2012).

Given the current scenario of insertion of thermosolar generation in Brazil, this work describes a new outline of reflective surface, in order to achieve the required concentration using a low number of heliostats and reduce losses by spillage, increase the amount of energy absorbed and, consequently, the performance of the solar plant.

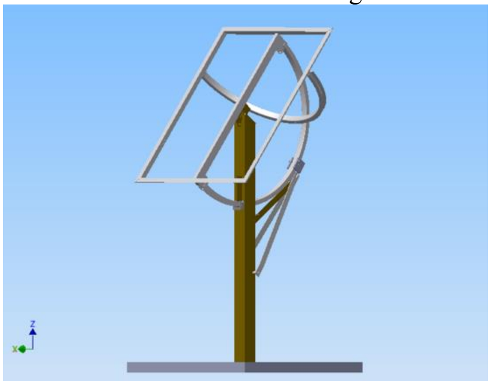
2 HELIOSTAT WITH ARC DRIVE

The first prototype heliostat with rim-motion on the horizontal and vertical axis was built by the German Aerospace Agency (Deutschen Zentrums für Luft- und Raumfahrt - DLR) (Pfahl et al., 2013). The drive parts have balanced weight that leads to low energy consumption. This was achieved only by means of the arch units acting as counterweights. The arches on the two axes make the connecting interface between the pestle and the frame that supports the mirror.

The heliostat tracks the Sun and reflects solar radiation to the receiver at the top of the tower in a solar power plant. They are considered the most important cost elements of a solar plant installation because they represent 50% of the plant's capital cost (Kolb et al., 2014). In addition, the use of adequate heliostats can generate reductions of up to 40% in energy losses (Kolb et al., 2007). The cost of the heliostat depends on the size. The materials, requirements for performance and configuration are the same for all heliostats (Blackmon, 2013).

The heliostat with arc drive is formed by mechanical components that provide support and allow movement in both axes (Fig. 1).

Figure 1 - Sketch of the heliostat with rim drive designed in Autodesk Inventor 2014.

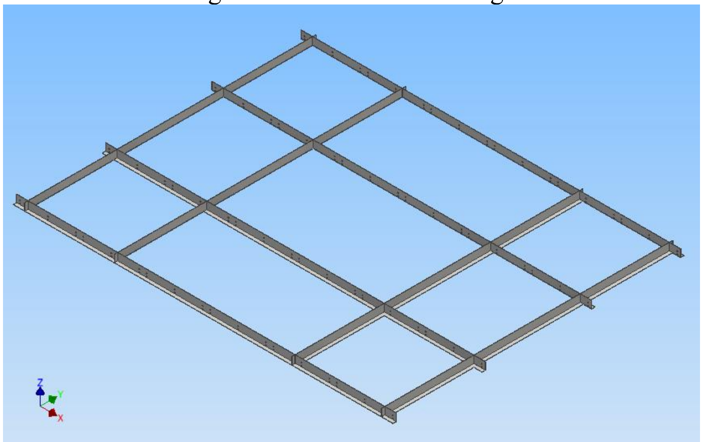


The term "suitable heliostat" refers to size, mirror configurations, operating load reductions, and wind load resistance (Coventry and Pye, 2014). Typically, the criteria for heliostat design depend on the environmental conditions of the site (Pfahl et al., 2013). Therefore, the design and optimization process of the heliostat has a great importance in projects of solar plants with tower.

2.1 METAL FRAME

The proposed metal frame solution is designed to be embedded in the support structure of the drive system, suitable for the heliostat with rim drive, with the minimum of steel used, but that supports the surface weight of the reflector. The developed configuration allows all three types of connections to be used (Fig. 2).

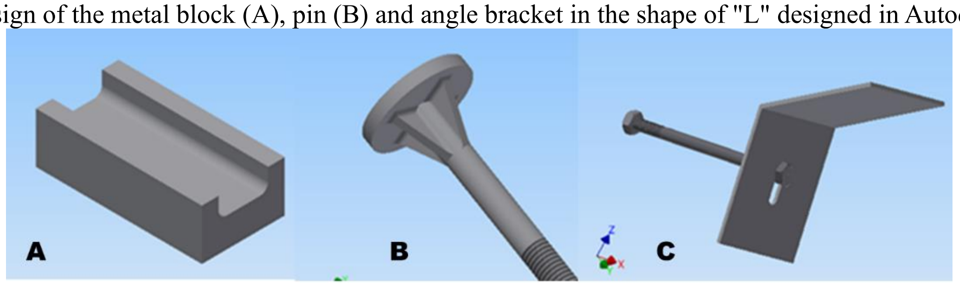
Figure 2 - Metal Frame Design



2.2 PROPOSALS FOR CONNECTING ANGLES

Connection proposals were created to make the connection between the steel structure and the reflective surface. The connection models analyzed were designed to fix the mirror strips and provide the desired curvature. In this sense, three connection options were proposed (Fig. 3): metal block, pin and L-shaped angle.

Figure 3 - Design of the metal block (A), pin (B) and angle bracket in the shape of "L" designed in Autodesk Inventor.



2.3 MIRROR SKETCH

The mirrored surface of the most modern heliostats are thin mirrored glass, with low iron content for greater reflectivity, greater resistance to oxidation, and therefore greater durability. Concentration is achieved through the use of fashionable positioned mirrors to concentrate the direct radiation flow on the receiver. The geometry of mirrors alters the analysis of the behavior of the heliostat field, allowing it to be modeled by a series of stages, composed of optical elements that possess certain attributes, including shape, contour, and optical quality. To achieve the best concentration factor, a reflective surface shape with curvature was proposed to obtain the focal length and offer the best concentration factor (Fig. 4), divided into six (6) curved mirror strips, required based on the 30-meter focal length between the receiver and the heliostats field (Fig. 5). Each heliostat has dimensions of 2.5 x 3.26 meters, with a reflection area of 8.15 m² formed by strips with dimensions of 2500 x 541 x 8.1 mm, which are composed of glass and mirror glued together.

Figure 4 - Heliostat adapted to tropical latitudes.

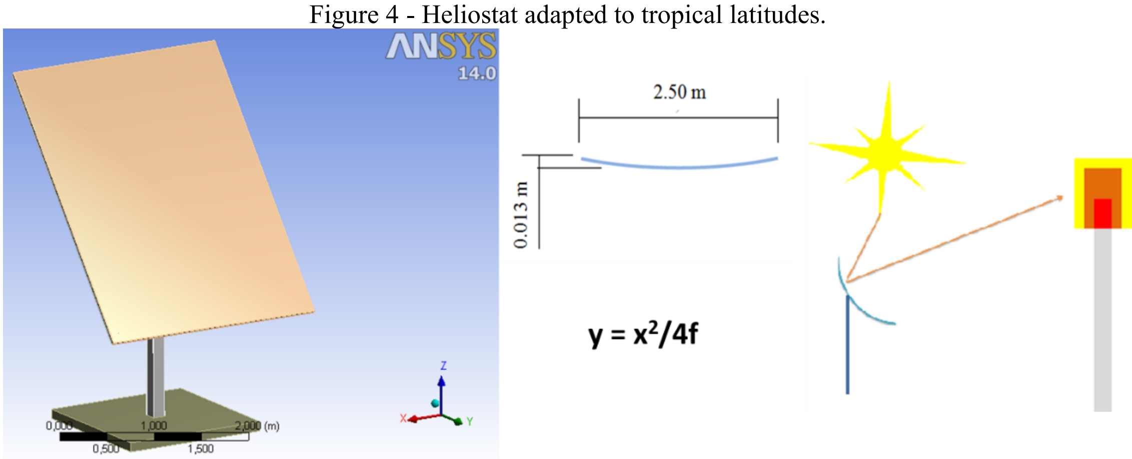
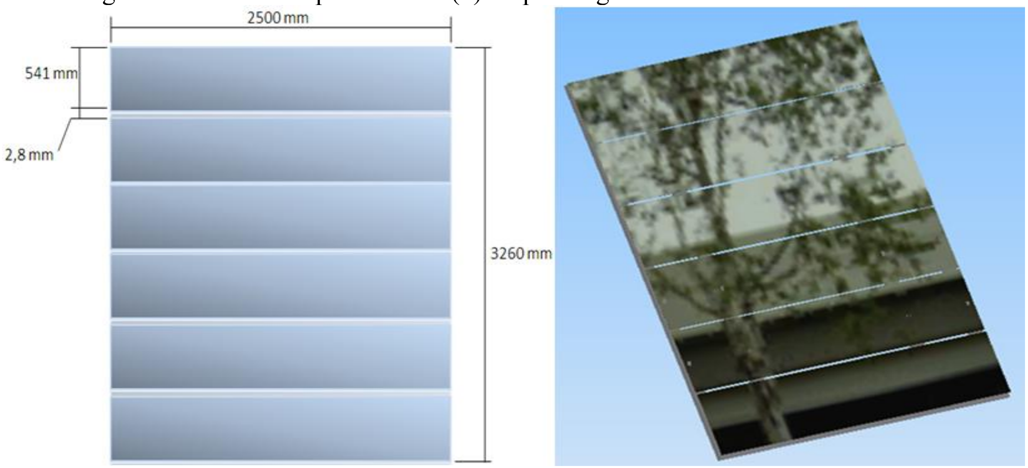


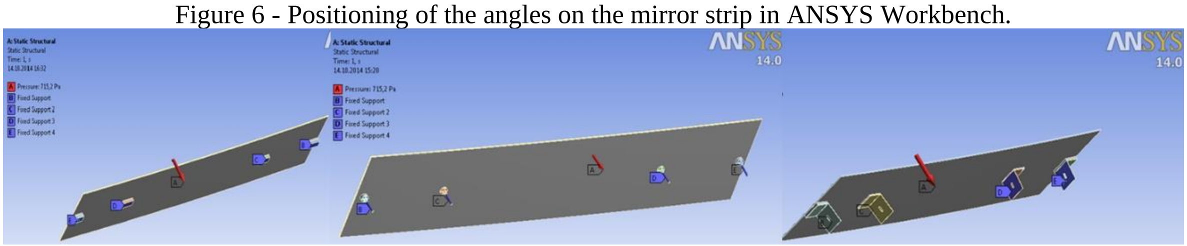
Figure 5 - Mirror composed of six (6) strips designed in Autodesk Inventor 2014.



3 STRUCTURAL ANALYSIS

The sketch of the reflective surface composed of six horizontal mirror strips was designed using the Autodesk Inventor program and submitted to structural analysis by the Finite Element Method (FEM) with the ANSYS Workbench version 2014 program. Each evaluation was performed with one of the three connection options. The applied wind load corresponds to a pressure of 715.2 Pa at 25°C and air density of 1.184 Kg/m^3 (Fig. 5). Hourly wind speed data were measured during the period 1989-2008 using an anemograph IH Wilh Lambretht Haringen TYP.1440 Nr: 351873, installed at the UNESP/FCA Climatological Station (22.85ºS, 48.43ºW, 742 m). The analyses were made at the Solar Institute of Jülich - Germany. In the structural simulations, a wind load that can occur in São Paulo was applied (29.9 m/s) in order to predict the deformation and stresses (Von Mises) caused by the action of the winds under the mirror strips. The precise calculation of the wind load is the key to the structural design of the heliostat. Wind loads are usually analyzed using wind tunnel tests, numerical simulations, and experiments on real heliostats (ZANG et al., 2011).

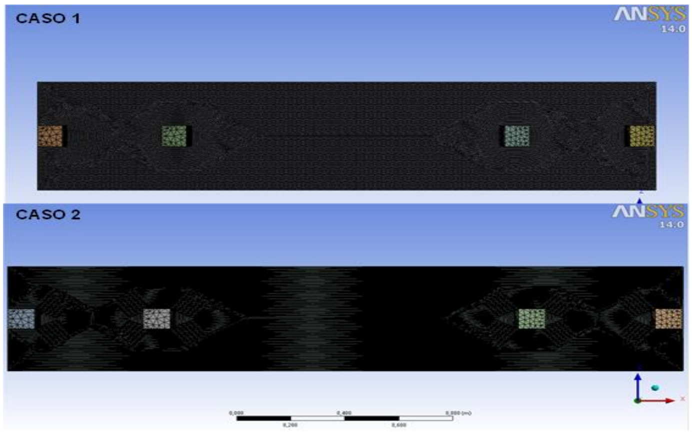
Figure 6 - Positioning of the angles on the mirror strip in ANSYS Workbench.



The meshes were created based on two methods, with different applications in different parts. In the angles, the method used was the Tetrahedron (triangular elements) because one of the pieces contains holes and nonlinear conformation. For the mirror strips, the method used was the "Size" (square elements), which is the specification of the size of the mesh. The use of square elements instead of triangular elements reduces the number of equations and consequently the computational work.

In order to evaluate the structural behavior of the glass strip as a function of wind load, two thicknesses (case 1 and case 2) were proposed (Fig. 7). In this case, 1 the thickness of the composite strip (adding glass and mirror) was 7 mm, as a way to analyze a safer condition. However, the situation analyzed for case 2 was one of a composite strip, with a more vulnerable condition from the structural point of view, with 4 mm thickness. Glasses are fragile materials, and fracture occurs at lower stresses in tensile than in compression. (BOURHIS, 2008).

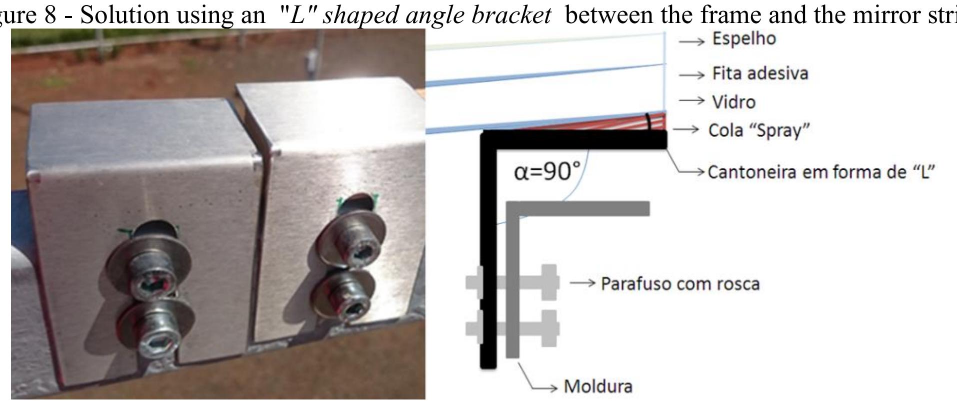
Figure 7 - Mesh obtained by the symmetric method (for the strip) and tetrahedron method (for angle) in the same simulation for cases 1 and 2.



4 FINDINGS

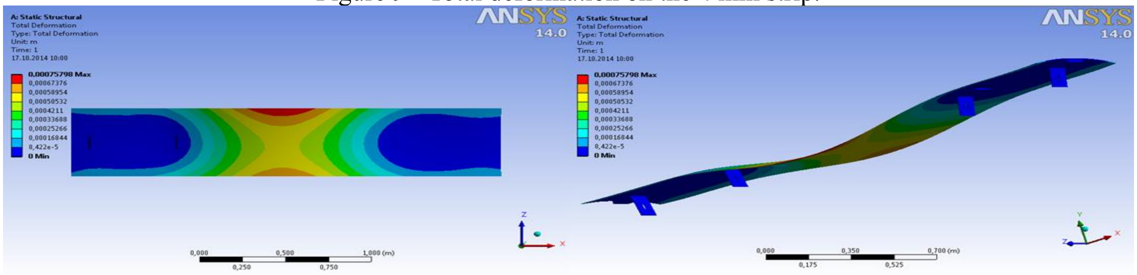
The best connection option found was the "*L"-shaped angle*, as it allows the height of the curvature of the mirror to be regulated through a prolonged hole in the structure of the piece and a screw. The established geometry requires low amount of steel and simple handling during installation. The angle bracket has a thickness of 3 mm, a height of 100 mm and a length of 100 mm (Fig. 8). Each mirror strip is connected to the frame by means of 4 angles, initially.

Figure 8 - Solution using an "*L" shaped angle bracket* between the frame and the mirror strip.



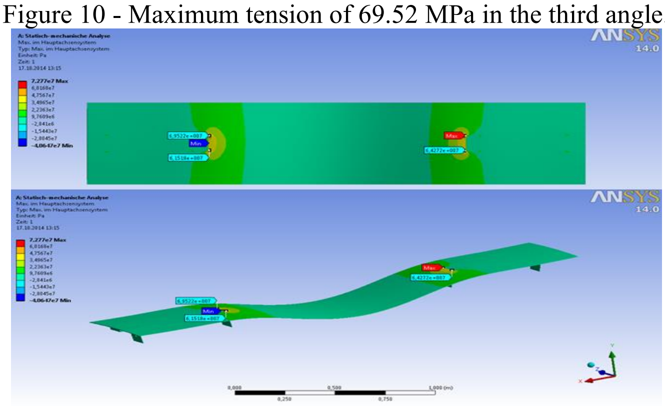
The results obtained through the computational images express the behavior of the composite strips, by means of colors that indicate the variation of the deformation and tension. The analyses confirmed that the strips with 7 mm thickness are oversized and were resistant to deformations. However the exorbitant amount of material makes the option unfeasible, due to the cost of manufacture and the weight that it exerts on the support frame of the mirrors. The strips with a thickness of 4 mm showed acceptable values of 0.75 mm of deformation (Fig. 9).

Figure 9 - Total deformation on the 4 mm strip.



However, the analysis of maximum main tension in the 4 mm strip showed a value of 69.52 MPa in the third angle, close to the movement frame (Fig. 10).

Figure 10 - Maximum tension of 69.52 MPa in the third angle.



The maximum main voltage value of 99.77 MPa (Fig. 11) was observed in the two central angles near the movement system. The tension values are excessive near the connecting angles between the frame and the mirror strip (Von Reeken et al., 2011).

Figure 11 - Maximum voltage of 99.77 MPa in the central angles.

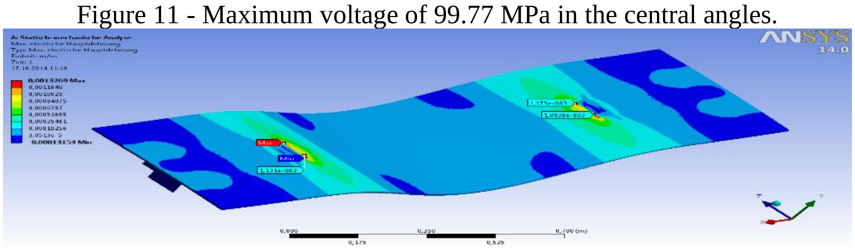
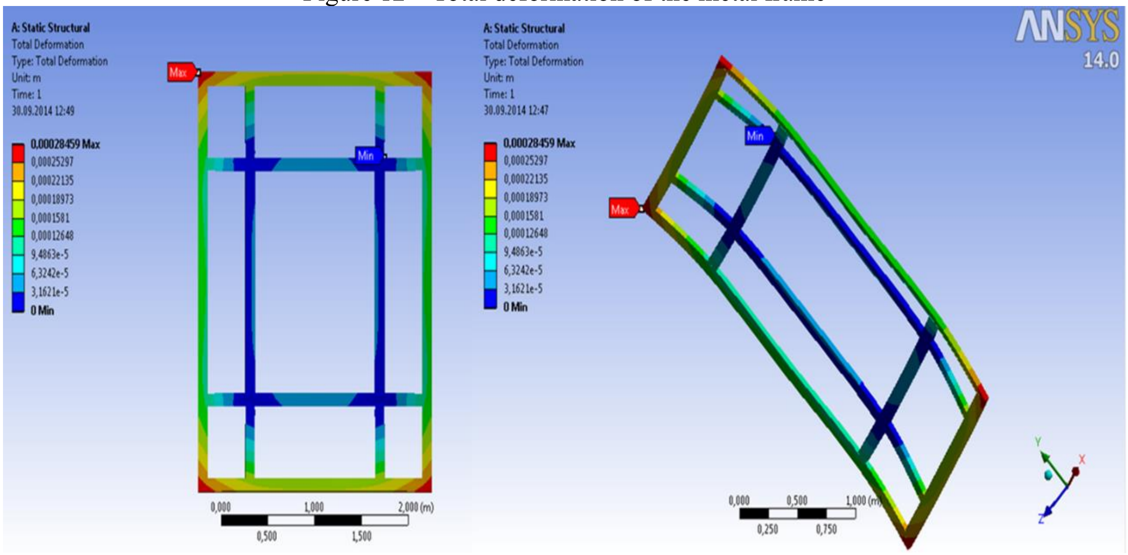


Figure 12 – Total deformation of the metal frame



After the structural analysis of the mirror strips was carried out, methodologies were established for the assembly of the reflective surface by means of alternatives with the best assembly sequence, from the point of view of manual ease and that offers less risk of possible damage to the mirror and glass.

5 CONCLUSIONS

The small heliostat with the reflective surface divided into strips allows less handling for assembly and installation, simple tracking system and with lower cost (better supports the wind load) and a better use of the terrain. The 4 mm thick mirror strip proved to be a good option from an optimum point of view, but susceptible to significant stress caused by the wind, near the central connecting angles positioned next to the support of the drive system. Consequently, it was necessary to redistribute the connecting angles in order to reduce the pressure load on the mirror. For this, the number of angles per strip went from four to twelve (Fig. 13).

Figure 13 - Increase in the number of angles per mirror strip.

In addition, an option to connect the mirrors to the frame through an L-shaped connection angle bracket that allows the curvature of the mirror to be regulated, requires a low amount of steel, simple handling during installation and allows the possibility of adjusting the mirror(s), even when already installed to the structure (Fig. 13).

The best assembly sequence of the reflective surface of the heliostats (Fig. 14), from the point of view of ease of handling, was as a first step, gluing the L-shaped angles to the mirror strip and only then fixing them in the metal frame and positioning them with the desired height of curvature.

Figure 14 – Establishment of the best assembly procedure.

The strip composed of glass and mirror proved to be rigid enough to resist the tension in the outermost connectors and flexible to provide the height of curvature of the parabola (Fig. 15).

Figure 15 - Heliostat with optical surface composed of 6 curved mirror strips.

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