MODIFICATIONS TO 25m^2 TARGET-ALIGNED RESEARCH HELIOSTAT MIRROR PANELS

Thomas H. Roos[1], Frikkie Rossouw[2], and Louw van Zyl[3]

[1] M. Eng. (Mech), Principal Research Engineer, CSIR (DPSS), P O Box 395, Pretoria 0001, South Africa,
Phone: +27 12 841 2329, Fax: +27 12 349 1156, E-Mail: throos@csir.co.za.

[2] Senior Ground Vibration Test Technician, CSIR (DPSS),

Phone: +27 28 425 3919 , Mobile:+27 72 455 1530

[3] M. Eng. (Mech), Principal Research Engineer, CSIR (DPSS), Phone: +27 12 841 2715

Abstract

Several heliostat mirror panels of the CSIR 25m^2 target-aligned heliostat suffered corrosion-related failure, prompting a panel redesign. Two test samples of the new design were subjected to mechanical and thermal cycling tests in an attempt to simulate accelerated life loading, as well as simulated hail testing. While the samples survived all tests without failure, the results are not fully conclusive as the mechanical cycling and hail test sample was manufactured of 4mm instead of the design 3mm mirror sheet. The test results nonetheless suggest that a sample made of 3mm mirror sheet would successfully survive the tests, and preparations for such tests are underway. Conclusive thermal cycling tests require a reduced scale mirror panel to be manufactured and tested in an environmental test chamber.

Keywords: heliostat, mirror, mechanical cycling, thermal cycling, hail

1. Introduction

A 25m^2 target-aligned research heliostat (see Figure 1) has been developed at CSIR [1] to provide the concentrated solar flux for volumetric receiver development studies. During the operation of this heliostat, several shortcomings have been identified, two of which will be addressed in this paper.

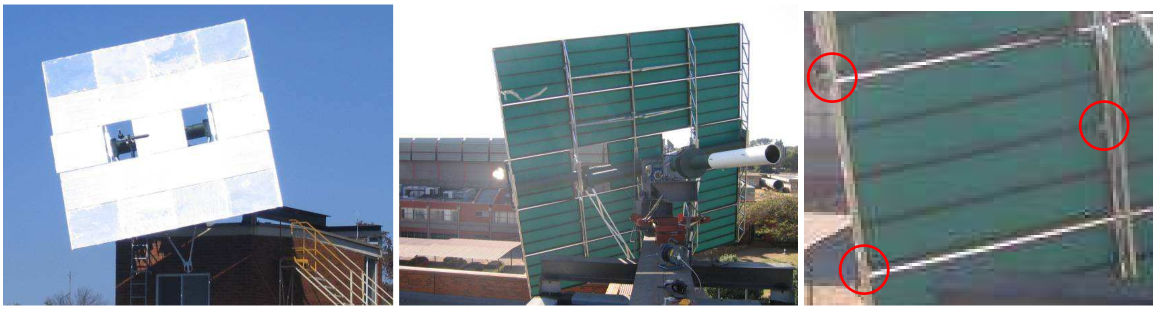

Figure 1: Front (left) and rear (centre) views of heliostat, close-up of mirror panel showing reinforcing stringers and three attachment studs (right)

Firstly, the 36” satellite dish actuator (which controls the pitch or quasi-elevation motion of the heliostat) at times decreases actuation speed when returning the mirror array to the horizontal stow position (indicating a load near the motor torque limit), and occasionally stops (probably due to the motor overheating). This actuation difficulty is due to the combined weight of 19 mirror panels, each 21 kilograms, at a moment arm of about 120 mm when vertical (giving a torque of 470Nm) combined with the unknown frictional torque of the hygroscopic engineering plastic bearings.

Secondly, some of the mirror panels were destroyed in wind storms of 17 October 2007 and 16 March 2008.

This was found to be due to two contributing causes:

- The 3 support backing stringers on each panel (visible in fig 1) were affixed to the back of the mirror glass but by oversight not to the outer frame, resulting in the weight of these stringers being supported by the mirror glass and not by the frame
- Despite the fact that the mirror frames had been painted (after the mirrors had been bonded to them), corrosion of the frames nonetheless took place. This corrosion propagated under the frame/resin bonding interface, leading to mirror panes separating from the frames.

Since the heliostat is mounted on the roof of a 2-storey building, all the remaining mirror panels were taken down for safety reasons. It was decided to redesign the mirror panels with aluminium frames.

The original mirror panel design comprises a 1.25m × 1m × 3mm commercial mirror sheet, bonded to a rectangular frame welded from 25mm mild steel square tubing, with backing support stringers of mild steel rectangular tubing (25mm × 12.5mm). Mirror curvature was obtained from physical deformation before bonding over formers laser-cut to the correct parabolic shape. The panel is supported by three studs, two at either end of one of the short sides of the panel and the third halfway along the other short side (see figure 1).

The replacement frame design has the same outer dimensions in length and width, but is noticeably thicker. The short outer sides of the rectangle are made up of 38mm aluminium square tubing, which are welded to the 32mm aluminium square tubing that makes up the long outer sides. The stringer design was changed from rectangular tubing to sections from the construction industry, made from 0.4mm galvanized sheeting folded into 38mm sections. The stringers were riveted to the frame, making the frame and stringers a single rigid structure. Using laser-cut formers, the mirror sheet was deformed to a spherical curvature (of 66m focal length) and bonded to the frame and stringers. The new mirror panel mass is 14kg compared to the old panel mass of 21kg. It was expected that the new mirror panel design would alleviate both the corrosion and the actuator problems, since:

- aluminium forms a protective oxide layer against ongoing corrosion, and
- the mirror panel weight dropped from 21kg to 14kg. This reduces the mirror panel assembly maximum static torque from 470Nm to 313Nm.

It is clear that the original steel-frame panel deterioration was predominantly due to corrosion, but it is not clear whether the corrosion *caused* or merely *accelerated* the panel deterioration. Did the corrosion propagate from initiation sites alone or did thermal cycling (due to day/night temperature fluctuation) or mechanical load cycling (due to repetitive wind gusts during the storms) accelerate the crack propagation? The new panel design needed to be tested to settle this failure question.

Two test mirror panels of the new design were manufactured: one for mechanical cycling testing and one for thermal cycling testing. If the mirror panels passed the test, then corrosion could be safely regarded as the cause of the earlier failures. In addition, simulated hail testing was performed.

2. Thermal cycling testing

2.1. Thermal cycling test procedure

Unfortunately, the mirror panel is slightly too large to fit into the environmental test chamber at CSIR. Use was therefore made of a “hot box” (used by the wind tunnel staff to preheat wind tunnel models, balances and stings to wind tunnel steady-state temperatures) to subject the one mirror panel to repeated thermal cycling. The “hot box” comprises loose insulated panels which clip together around the wind tunnel model, sting and balance assembly in the wind tunnel test section. In this instance the “hot box” was assembled first and the mirror panel was lowered into it, taking care to separate the panel from the “hot box” walls using wooden spacers (see Figure 2). The thermal energy is supplied by two sets of three infrared lamps, which are used to heat the mirror panel frame from the sides. This is based on the assumption that in practice the solar radiation heats the frame rather than the glass (as the mirror reflects most of the radiation), and the frame then heats the glass by conduction through the resin bonding layer.

Figure 2: “Hot box” with one top panel removed showing mirror panel inside, with infrared lamps off (left) and on (right)

A controller monitors the target temperature (thermocouple attached to frame) and environment temperature (thermocouple attached to inside surface of hot box roof), and switches the lamps on and off until the frame reaches the target temperature (54˚C), all the while keeping the environmental air temperature in the hot box below 74˚C to prevent the glass being significantly heated by air convection. The wiring for the thermocouples and the infrared lamps can be seen in Figure 2.

As the structure temperature approached the specified test ceiling, the environmental temperature limit would automatically be lowered until a temperature balance was reached at 54˚C structural temperature. Once the desired temperature was reached, the heating system was switched off manually, one of the top panels of the hot box was removed and a desk fan was used to bring the environmental, as well as structural temperatures down to under 30˚C.

2.2. Thermal cycling test results

The mirror panel was subjected to 37 thermal cycles in total with no resultant cracks or delamination. All cycles began with the structure at or below 30˚C and ended at 54˚C (resolution 1˚C).

During the performance of test run number 26 the temperature of the structure was brought down to 15˚C by using dry ice with the cooling fan to circulate cold air inside the “Hotbox”. During test run number 33 the structure was exposed to a temperature of 54˚C for a period of eight hours without any cooling.

Test run number 37 was used as a thermal shock test. The structure was heated to 54 C and the mirror was sprayed with cold water representing raindrops. The mirror surface cooled down rapidly to the touch, while the mirror frame stayed at a temperature of above 50˚C for the duration of the test. No cracks or delamination could be detected by visual inspection after the thermal shock test.

3. Mechanical cycling testing

3.1. Mechanical cycling test procedure

The mirror panel is supported by three studs, to allow control of angular positioning. In high winds, the most likely vibration mode is torsion about the single stud (red axis in Figure 3), rather than simple bending along the long axis of the panel due to the stiffening effect of the stringers.

This was simulated by anchoring the three studs as shown and applying an oscillating force, using an mechanical exciter, at the one free corner as indicated by the red arrow.

The effect of storm wind loading was conservatively approximated, using the following assumptions:

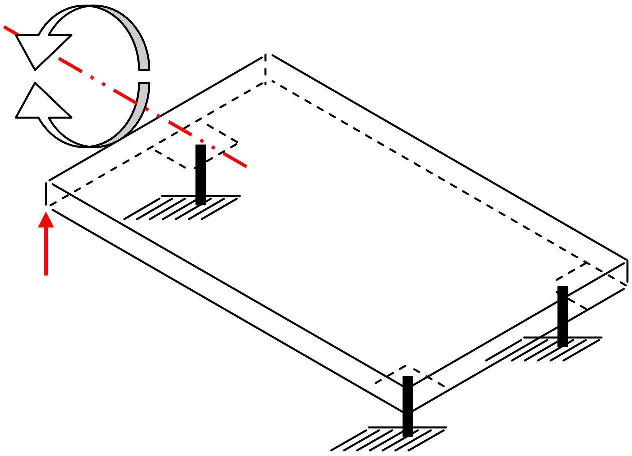

Figure 3: Expected mirror panel vibration mode

- A peak gust velocity of 43m/s (Pretoria 1 in 50 year storm strength for building design purposes) was assumed, with a gust factor of 1.6 [2], so the lower wind speed is therefore 43/1.6 = 27m/s

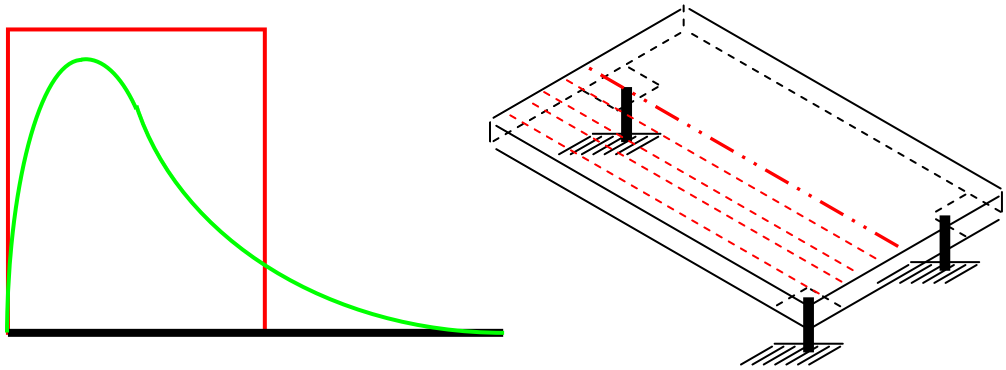

Figure 4: Wind loading approximation

- A finite element model of the composite mirror panel was constructed, with a conservative torsional wind loading distribution simulated by a stepwise lift coefficient distribution of 2 over the windward half of the panel and 0 over the leeward half (red distribution in Figure 4). This was done since an aerofoil near stall (worst load case) has a near-triangular lift distribution, with a peak lift coefficient of 1.8 at about ¼ to 1/3 chord length downstream of the leading edge (green distribution in Figure 4).

- A predicted displacement of 7mm of the unsupported mirror panel corner was obtained for a steady wind load of 43m/s. The displacement is proportional to the force exerted as the FEM model is linear. At a wind speed of 27m/s the corner can be expected to be displaced 2.7m/s. The mean displacement is therefore about 5mm.

- In order to get the test setup as close as possible to the original heliostat configuration during accelerated vibration testing, the mirror and frame was mounted onto a rigid I-Beam frame using the original M10 mounting bolts. A pre-test torsion load was applied to one bottom corner of the mirror using a spring system. This is to allow the exciter to oscillate about a mean exciter displacement of 0 (instead of a mean exciter displacement of 5mm) with the spring adding a constant preload of about 150 Newton. Figure 5 shows the test installation.

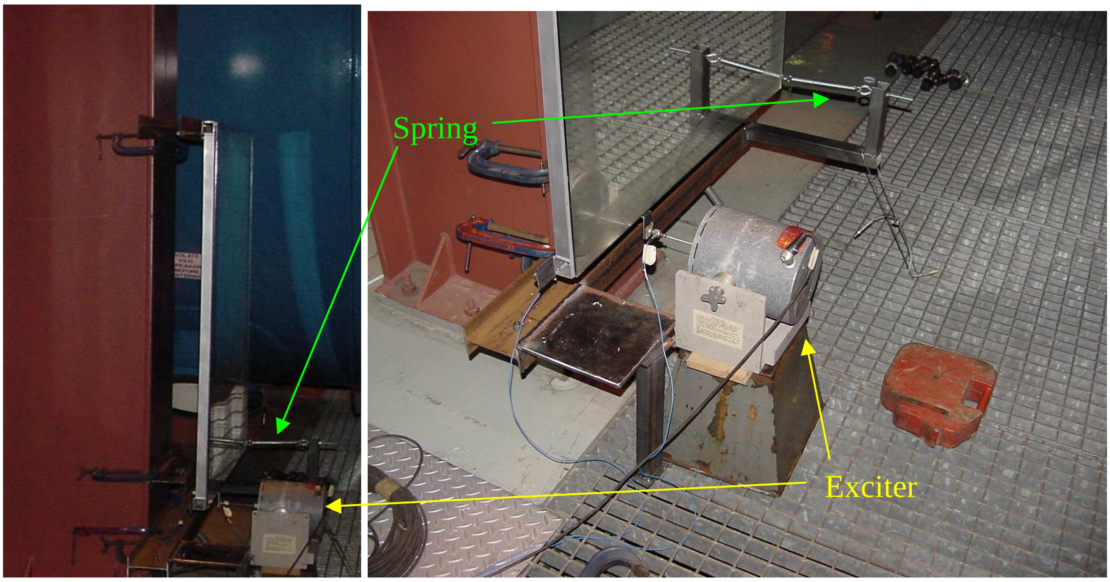

Figure 5: Mirror mounted on test frame (left), close-up of mechanical exciter installation (right)

A CSIR proprietary ground vibration test system was used to induce the vibration needed for the accelerated life vibration test. The system has the capability to control the response amplitude as well as tracking the natural frequency of the test piece. A change in natural frequency would constitute an indication of structural failure. The input force level was measured using a PCB force transducer, and the acceleration was measured using a PCB accelerometer.

3.1. Mechanical cycling test results

The first natural torsion frequency of the mirror panel was experimentally determined to be 17.13Hz. The mirror panel was vibrated at this torsional frequency, controlling displacement (maximum corner displacement of 4.6 mm) rather than force as the input variable. The panel successfully survived 1 000 000 cycles. The natural frequency varied only in a tight range of 17.122Hz to 17.150Hz (0.16% of nominal value), and the starting and frequencies differ only in the 3rd decimal place, so no damage is expected.. A visual inspection of the mirror, mounting frame, and interface bond did not show any signs of vibration damage or de-lamination and cracking.

4. Hail testing

4.1. Hail test procedure

The hail specification given for large-area heliostats [3] is survival of impact of 1 inch (25.4mm) diameter hailstones travelling at 75 fps (22.9m/s), an impact energy of 4.13J. The South African standard for hail testing of mirrors and glass is survival of the impact of a 38mm hail stone at 20J and 30J, and the extreme condition 25 year storm test criteria is survival of the impact of a 45 mm hail stone at 20J.

Figure 6: Pneumatic hail gun

Hail impact tests were performed with the aid of a CSIR-designed pneumatic hail gun, used for testing elements for the construction industry. The hailstone sizes used were ice spheres of 20mm, 38mm and 45mm diameter. The test setup ensured that the test hailstones would impact perpendicularly to the mirror surface. All shots were fired at close range to maximize the impact and accuracy of projectile speed readings. The pneumatic hail gun can be seen in figure 6.

4.2. Hail test results

As shown in Table 1, a range of hailstone sizes and velocities were tested on the mirror panel. The final test made use of a 45mm diameter hailstone at 78m/s. The mirror panel withstood the 243J impact without any damage to the surface (as illustrated in figure 7), as it had survived all the previous hailstones. For comparison, the hailstone density implied by the true mass and nominal diameter is given, as well as the implied diameter for the true mass and ice density of 916.8 kg/m^3.

$D_{nominal}$ (mm)	Mass (g)	$\rho_{implied}$ for $D_{nominal}$ (kg/m^3)	$D_{nominal}$ for density of 916.8 kg/m^3 (mm)	Velocity (m/s)	Impact energy (J)
20	3	716.2	18.42	82	20.17
20	3	716.2	18.42	69	14.28
20	2.7	644.6	17.78	75	15.19
20	2.7	644.6	17.78	57	8.77
20	3.1	740.1	18.62	80	19.84
38	26.1	908.4	37.88	18	8.46
38	26.2	911.9	37.93	45	53.06
38	26.6	925.8	38.12	38	38.41
38	27	939.8	38.31	54	78.73
38	26.6	925.8	38.12	50	66.50
38	26.4	918.9	38.03	25	16.50
45	39	817.4	43.31	40	62.40
45	39.2	821.6	43.38	62	150.68
45	40	838.3	43.68	78	243.36

Table 1: Hailstone sizes and velocities tested

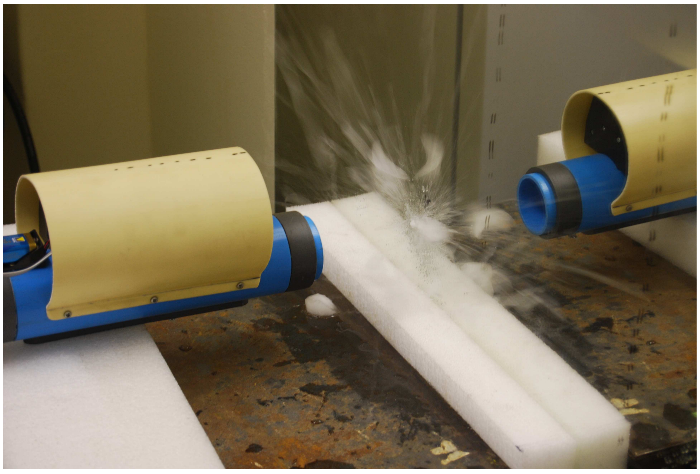

Figure 7: Impact of 45 mm hail stone at 78 m/s

5. Conclusions

After the tests described in this paper had been completed, it was discovered that the mirror panel used for the vibration tests and hail tests had in fact been manufactured from a 4mm mirror glass sheet as opposed to the design 3mm glass sheet. The 3mm panel is therefore now being prepared for the vibration and hail tests.

As the 4mm mirror panel had been excited to the calculated 3mm panel displacements for the storm wind limits of 43m/s and 27m/s, it had been tested to effectively much higher wind loads as the 4mm panel is stiffer than the 3mm panel. It is therefore believed that the less stiff 3mm mirror panel will similarly pass the accelerated life test.

Similarly, the fact that the 4mm panel passed the hail test at impact energies so much higher than the specification similarly gives confidence that the 3mm mirror will at least meet and probably exceed the specifications.

The 3mm panel survived the limited thermal cycling tests performed upon it: cycling from ambient to 54˚C and thermal shock. A temperature difference of only 25˚C, however, does not prove that the mirror interface with the frame can withstand extreme climactic changes, and 37 cycles do not constitute a conclusive test. Ideally the temperature fluctuation test should be carried out in the environmental chamber where temperature differences between minimum and maximum can be programmed to be from -10˚C to +50˚C at least, for a substantial number of cycles. As the mirror panel design is about 15% too large to fit into the environmental chamber at CSIR, a reduced scale mirror panel will be manufactured for sustained, automated thermal cycling testing.

The new mirror panel design has withstood all environmental tests carried out so far, but a conclusive result requires the 3mm mirror panel to have passed the mechanical and vibration tests and extensive thermal testing.

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