Composite Curved Laminates for the UNSW Sunswift II Solar Array

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Abstract

The aerodynamic form of the UNSW Sunswift II solar racing car is, perhaps simultaneously, its key feature as well as its greatest manufacturing challenge. While improving the aerodynamic performance and total collector area, the complex curves pose a significant challenge in the design and construction of a solar array over its surface. Curved solar panels present an interesting problem in terms of construction, and their electrical characteristics. These issues are considered and the solutions employed in the development of Sunswift II, given. The resulting array is shown to be close to the required specification, and the conclusion made that the process should be repeated for future projects.

1. INTRODUCTION

The UNSW Solar Racing Team has been involved in designing, building and racing solar cars since 1996. The team competed for the first time in the 1996 World Solar Challenge (WSC) from Darwin to Adelaide with their entry *Sunswift* (formerly the *Aurora Q1* solar car[1]). Early in 1997 the team embarked upon the arduous task of designing and building a totally new car named *Sunswift II*.

During the initial conceptual design of the car several issues were identified as being critical. One of the most important, was the integration of the aerodynamic shape of the car with the solar array. Typically 70% of the energy expended by a solar car during a WSC race comes from aerodynamic drag and between 80 to 90 % of the energy used in a WSC comes from the array (the rest coming from the initial battery charge).

The rules of the WSC state that the allowable size of the car must fit within a box of 6m long x 2m width x 1.5m height and that the array must fit within a box of 4m long x 2m width x 1.5m height. A long-car design using the full dimensions of the box rule, generally consists of the driver being packaged in the first 2m length of the car and a reasonably flat array at the back of the car. Several previous teams, however, have chosen a short-car design where the driver and driver's canopy is packaged within the solar cell area. The main advantage of such a design is that it reduces the overall aerodynamic drag of the car by reducing the wetted surface area and thereby reducing the skin friction component of drag. Other advantages include a potentially lighter and more manageable car. The disadvantage with a short-car design is the difficulty in building an array on and around the driver's canopy where complex curves are generally needed.

Taking these considerations into account it was decided on a short-car design and to find an appropriate array manufacturing technique to avoid the problems associated with the aerodynamic curves. The final design consisted of a 4.5m long car with a frontal area of 0.85m2 with composite curves used to fair the driver's canopy into the main aerofoil shape of the car. (See Figure 1) The rounded edges and faired in canopy were designed to minimise the effect of cross winds during the race.

Figure 1: UNSW Sunswift II's shape gives excellent aerodynamic performance

From previous race experience and general design considerations several objectives were identified as being critical in the design of the array and cell encapsulation technique and included:

1. The surface should deviate from the intended shape by no more than 0.5mm in any region, and there should be no discernible steps larger than 60µm.
2. The cell performance losses via any encapsulation should be minimised, and less than 5%.
3. The cells should be protected from under likely race conditions. (e.g. flying rocks, dust, etc…).
4. Mass should be within $2kg/m^2$.

Two array manufacturing techniques were trialed for the 1999 WSC and although each design met some of the design criteria, neither technique fulfilled all of the above objectives.

The first method involved a lamination technique where flat strips of cells were laminated between layers of fibreglass with epoxy resin and then bonded down to a structural skeleton. The cells used were BP Solarex "Saturn" cells with a minimum cell efficiency of 16.5%. This manufacturing technique resulted in an extremely light and stiff array where two people could easily lift it off the car. However, problems associated with the technique included optical degradation of the epoxy resin, some cell cracking when bending around the composite curves of the car (during the bonding process) and electrical mismatch due to the large cell sizes. Moreover, the strips would only bend in one direction, making it difficult to obtain a smooth, aerodynamic transition between strips.

The second method trialed for the 1999 WSC involved bonding down individual cells to the shell of the car and then covering it with a conformal coating. This avoided the problems of cell cracking and optical degradation. The BP "Saturn" cells were also cut down to approximately one-third of their original size allowing better electrical matching within panels. Covering the busbars by shingling the cells in one direction also allowed an increase in the total active area of solar cells. The main disadvantage that resulted from this technique was the surface finish which did not produce laminar flow over the front section of the car as desired.

Due to damage incurred to the solar array during a collision in the 2000 Sunrace, the team embarked on another campaign in early 2000 to design a new array for the 2001 WSC. Several different concepts were explored. This paper discusses the technique (and its development) used to construct the solar array which raced in the 2001 World Solar Challenge.

2. ARRAY CONSTRUCTION

It was decided very early in the development phase that the only reasonable way of attaining the shape and surface finish goals for our encapsulation technique was to form the panels in a female mould. It was also decided that a multi-layer laminate structure, as used in many commercially available photovoltaic modules, would be most appropriate. This consists of an elastomer, bonded to a hard outer layer.

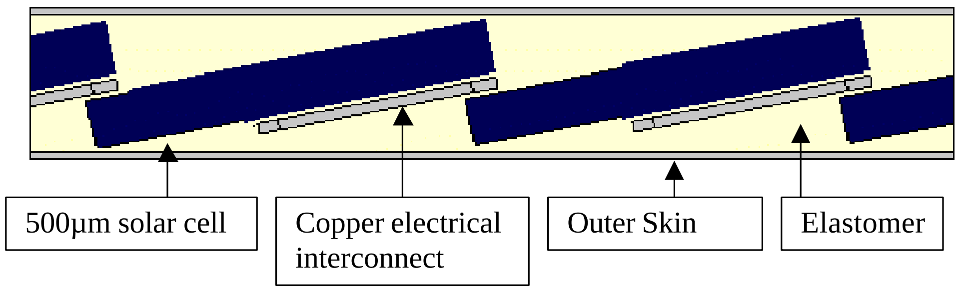

Figure 2: Multi-layer laminate structure

The elastomer provides protection against sharp impacts, as well as being flexible enough to allow thermal expansion of the solar cells. It does not provide any support for the completed module, other than acting as a spacer between the outer skins. These skins provide much of the panel's structural integrity.

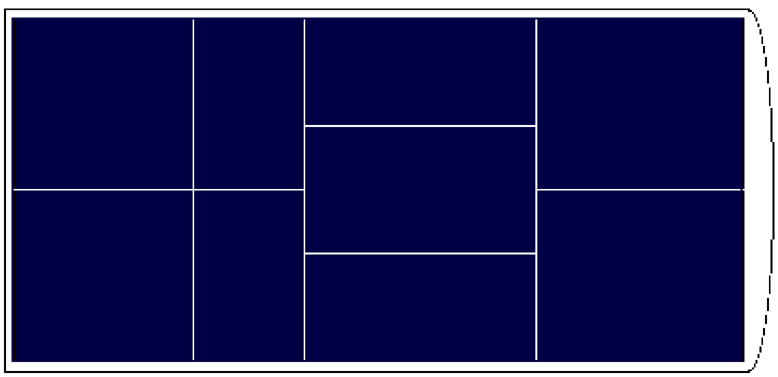

Figure 3: Sunswift II Panel layout

Nine panels were constructed (See Figure 3). A centre split, with eight panels in the main body of the car. The canopy formed the ninth panel. Each panel was about 1m^2. The splits were chosen that the section forward of the canopy should have no lateral splits (in order to avoid tripping laminar flow). Each panel was then sized to approximately 1m^2. The centre panel forms the canopy which is removable to become the driver's emergency escape route.

2.1. Materials Selection

A large number of materials were trialled. Initial experiments were made with a two-part clear silicone (Sylgard 184™) as the elastomer. This showed promise, as requiring the least amount of investment regarding lamination equipment since it did not require heating. The time related nature of its cure, however, proved to be a large practical constraint, since all work on the panel needed to be performed before the working time on the elastomer expired. A second problem was thickness control. Over a large area, it is difficult to spread an even thickness of the liquid elastomer. A third problem is the mating of the two parts (assuming a technique similar to that used for EVA is employed). When done outside of a vacuum, bubbles form in the silicone. Inside of a vacuum, it is difficult to place cells or alternately allow a male former (carrying the cells) to mate and allow bubbles to exit.

Late in 2000 the team focused on trials using EVA (Ethyl Vinyl Acetate) as the elastomer and met with much success when replicating the recommended lamination technique, for small, flat panels. To this, modifications were made to allow a curved panel to be produced.

Neither Silicone nor EVA elastomer is appropriate to be exposed to the environment as the outer layer of the laminate. An outer skin can provide structural support, and protection from dust, dirt, and impacts. If the refractive indices of the materials can be suitably matched, a skin can, somewhat counter-intuitively, reduce the overall optical losses of the encapsulation system. Several requirements were placed on the skin. First, it had to be mouldable, or formable in some manner; the panels were to be laid up in-mould above the pre-formed skin. Second, the optical losses resulting from the skin should be minimised via matching of the refractive indices, use of low-absorption materials and/or appropriate texturing of the surfaces.

A large number of skin materials and fabrication processes were trialled. Epoxy/fibrelass, Tefzel®, Teflon®, Tedlar®, polycarbonate, acrylic and Cytop® were all considered. All early lamination trials were conducted using 0.25mm polycarbonate sheet; which performed well. The intention was never to use this plastic due to its comparatively high reflective losses. In order to continue development of the lamination process, polycarbonate was formed over a male plug in the shape of the car. Attempts were made with Teflon® and Tefzel®, but moulding these extremely thin sheets proved to be unattainable within the time available. Also, when laminating to these thin sheets, wrinkles formed, even over small areas. This was deemed unacceptable. Time considerations and these reliability issues prompted the use of 0.38mm polycarbonate sheet. The optical losses were measured at approximately 4%, fulfilling the original goal of <5%. It is the opinion of the authors, however, that a more appropriate skin is likely to exist, and could be used in a similar manner to the method used for the polycarbonate.

2.2. Layup

The panels were laid active surface down in a female mould.

The polycarbonate sheet was pre-moulded over the positive form of the car. Deformations due to the moulding process proved not to be an issue since the panels were made small enough that the local differences in shape between the polycarbonate and the mould were negligible.

A symmetric layup was chosen such that differing thermal expansion coefficients between the cells and plastic should not cause warping. Therefore EVA of equal thickness and two identical moulded polycarbonate sheets were laminated on both active and inactive surfaces.

The thickness of EVA was chosen such that the cells would “float”, not coming into contact with either skin. This was done out of concern both for the finish of the skin, and for the integrity of the cells. Varying the thickness of the EVA according to the curves to be filled could reduce the weight of the laminate further. Using the current technique, the laminates have met the weight target.

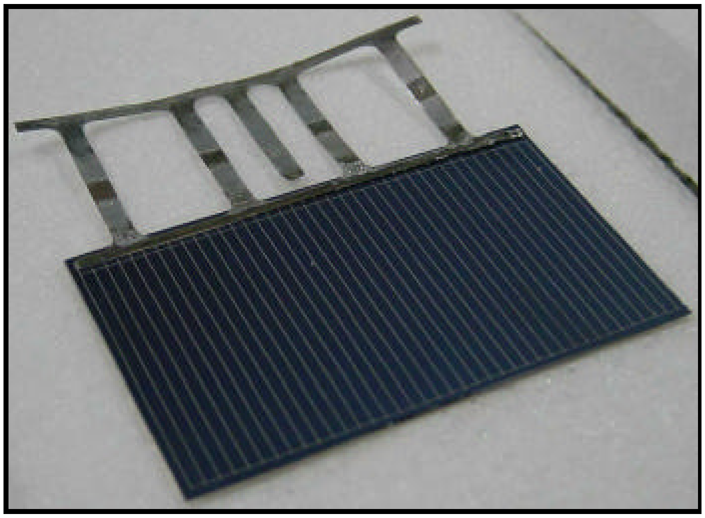

Figure 4: Topcell Buried contact solar cell, showing custom punched "H" interconnect with integrated test-lead.

Custom punched tabs were used for electrical interconnection between cells. Two varieties of cells were to be used. The solar cells used were approximately 62x35mm. In order to be connected in series along the shingle direction, a right angle tab was required. It is desirable to connect in the direction of the shingle to minimise the potential difference between adjacent solar cells, as well as reduce the number of insulators required (which are succeptable to failure). A ladder shape was eventually arrived at with an integrated fly-lead for testing purposes. The flylead was designed to be bent up at a right angle, and threaded through the rear layers of the encapsulation. Over 7000 cells were tabbed and re-tested following tabbing. Following this process, the cells were first soldered into groups of five or six depending on the string and array design.

The procedure, therefore, was firstly to lay the polycarbonate and front-side EVA in the section of the mould that corresponded to the panel to be produced. The sheets were cut oversize such that excess material could be trimmed following the panel's manufacture.

A strip of flexible polycarbonate was taped in place in the mould, aligned to the position of the row of cells to be layed. This was used as a ruler to line the cells in a straight line over the curve. When reaching the end of a row of cells, the shingle direction was reversed. This meant that wiring could be completed in a winding S-Bend fashion. This minimises the number of cable runs, reducing resistive losses and weight of the wire.

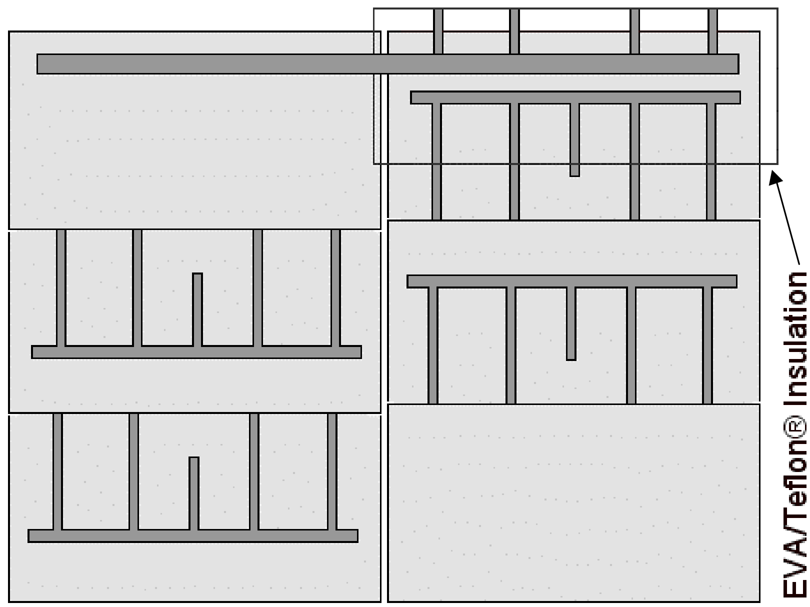

Figure 5: Interconnection scheme for a six cell string

Inter-row connections were formed by bending the tab from the front of the cell to be connected back on itself, insulating using Teflon®/EVA, and soldering a second piece of straight tabbing material across to the back of the appropriate cell.

Many small electrical panels were constructed within the large physical panels to minimise the problem of angle mismatch. Angle mismatch occurs in curved solar arrays because cells in series strings may be subject to differing light intensities due to different orientations (on the curve). These small blocks of approximately thirty cells were insulated from the cells in the neighboring blocks by using a small piece of Teflon® and an accompanying piece of EVA. These were placed between the shingle to be insulated. Less than 0.5% of the insulators used have been found to have failed due to movement of this Teflon®/EVA.

Once all electrical connections were made, the rear-side polycarbonate and EVA were marked with the positions of the flyleads present on each tab, the flylead exit holes punched, and the leads threaded through the sheets.

2.3. Lamination

A four tonne vacuum chamber was constructed for use in the manufacture of the solar array. A high-temperature fibreglass mould had been built for use with high temperature composites (in other parts of the car). This mould formed part of the vacuum chamber. 12mm thick, 200mm wide, steel hoops were bonded every 200mm to a steel frame surrounding the edge of the mould. 600 T-pieces were bonded to the rear of the mould's surface. 3mm steel plate formed a structural link between the hoops and the T-pieces. 3mm steel skins were then welded to form a vacuum chamber.

Figure 6: Vacuum chamber/mould used for lamination

Once a panel had been layed in the mould, it was bagged in a similar manner to that used for aircraft composites. A thin, flexible plastic bagging material is sealed around the edge of the part using vacuum tape.

Figure 7: Vacuum bagging materials form an airtight membrane surrounding the part

During lamination, the air is evacuated from both the chamber and vacuum bag at the same rate. Therefore there is no differential pressure, and therefore no force on the fragile cells. When the part has risen to at least 85° (the temperature at which the EVA has outgassed, and become liquid enough to conform to the cell's shape), air is released back into the vacuum chamber, squeezing the layup into a thin laminate.

Following the application of pressure, the temperature is further elevated in order to cause the EVA to cross link, or cure. By this process the EVA is permanently hardened and will not soften under its heated operating conditions.

Experiments were performed to obtain the appropriate temperature to allow air back into the chamber, and the appropriate length of time and temperature to cure for/at. There are a variety of factors that affect these parameters, and the cure schedule will be different for most equipment.

The vacuum chamber/mould was heated using an oven at the facilities of Boeing Australia. A concern was had that the vacuum would thermally insulate the mould's surface. This proved not to be so. Temperature gradients caused by differing rates of heating did cause some issues however. The temperature rise at any point seemed to be related to its distance from the flat lid that formed one wall of the vacuum chamber. Following experimentation a set of temperature "windows" were developed for the various critical stages of the lamination; with all sensors (at different points in the laminate) required to lie between the upper and lower bounds in that window for the event to be initiated.

2.4. Final Assembly

Following the lamination, the panels were trimmed back to their desired shape and size. Using a release film, and PVA release agent, the front surface was sealed. The panels were then arranged face down in the female mould using a weak double sided tape to fix the panels in position.

The panels fit very well to the mould. Very little distortion had occurred between each panel's removal from the mould, and its repositioning.

An epoxy based bog was used to seal the edges of each panel. A carbon fibre structure was built over the rear of the panels. This structure formed a skeleton of support on the rear of the panels. Fibreglass was used as an external layer to insulate electrical connections from the conducting carbon fibre.

The structure was then removed from the rear of the panels. Some final wiring was effected prior to the structure's attachment. Added reliability in the insulation of the panels was provided by Kapton® tape over any exposed, electrically active component or area.

The entire assembly was then attached to the rear of the array using a silicone like adhesive.

The remainder of the structure was added and the bottom shell of the car mated. The entire array was released from the mould, bogging, fairing and painting completed. Installation of maximum power point trackers and other hardware such as indicators and telemetry, then occurred.

3. RESULTS

The array took ten students a total of 7000 person hours to complete. In approximate terms, each panel involved four students for 48 hours in shifts. The vacuum mould constitutes three months work for three people. Tabbing, pre-stringing and testing involved 5 students for a total of 1000 hours. Development work accounts for 1000 hours.

The final results obtained may be best presented when compared to the original goals:

5. *The surface should deviate from the intended shape by no more than 0.5mm in any region, and there should be no discernible steps larger than 60µm.*

   Locally the two panels forward of the canopy had no discernable steps. Fulfilling the second criteria, and allowing, conceivably, laminar flow over that section of the car.

   Thermal expansion gave rise to two major issues. Over time and use in the 2001 World Solar Challenge, a number of deviations became evident. The main cause of this was the themal expansion of the polycarbonate plastic. Rapid cooling then set the shape of the panels. This gave rise to a bulging effect between the rigid stiffeners on the rear of the panel where it was constrained.

   Another type of defect due to thermal expansion problem occurred during the lamination itself. The polycarbonate expanded during the lamination process but was restrained by the vacuum bag. This caused the plastic to "give" locally, causing small, well-defined wrinkles in the front skin. This appeared only to be a problem over the concave sections of the car, and so was limited to the rear of the canopy, and the canopy itself. One small wrinkle also appeared in the front left hand corner of the car. This was very likely due to misplacement of the polycarbonate sheet.

   It is likely that many of these COTE difference issues could be resolved via the use of an alternate front skin material. The SRT investigated a number of options, but used a material that was known to have problems due to time constraints.

6. *The cell performance losses via any encapsulation should be minimised, and less than 5%.*

   Four cells were encapsulated using the technique described. The cells were characterised before and after encapsulation. Their short circuit currents were then compared. Less than 5% losses were observed on these test cells, and an average of 3% for all cells tested was shown. These results are in no way conclusive, but give an indication of the performance degredation due to the cell's encapsulation.

   The entire array was estimated to produce approximately 1500W after encapsulation, and has been measured at 1450W before power point trackers, when temperature and illumination corrected. The difference is very likely due to effects of the encapsulation process such as handling during layup and breakage under the pressure during lamination.

7. *The cells should be protected from use in the race. (e.g. flying rocks, dust, etc…).*

   No observable power degradation has occurred during the 3000km of the World Solar Challenge. The thermal expansion issue continues to warp the panels, but can be minimised via cooling of the array.

8. *Mass should be within 2kg/m^2.*

   Once completed the solar array weighs approximately 80kg. Unfortunately the panel mass was not determined before the structure was attached. It is the author's estimate that the panels themselves weigh approximately 20kg of the total weight. Bringing the mass of the panels to 2.25kg/m^2. Removing weight from the structure, and using a lightweight option to bond the panels to the structure could reduce the total mass of the array. The wire size could also be reduced. Most aspects of the array were over-engineered in order to maintain reliability, although with more care substantial weight savings could be made.

   It is also the estimate of the authors that much of the weight resides in the cells and tabbing material themselves. Over 4kg of Tabbing material and 1kg of solder resides in the array. The silicon itself forms a large proportion of the total panel mass. Since 500µm thick cells were encapsulated, the amount of EVA used was large. If an alternate material were used, it is possible that the thickness of the front skin could be reduced, saving both weight and improving optical transmission.

4. CONCLUSION

Double curved laminates have been shown to be effective, and reliable. While time constraints limited the investigation into alternate materials and their fabrication, the materials used performed well.

If the team were to construct a new solar array, it is likely that a similar technique would be used.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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