Design, Manufacture and Construction of Shadehouse Structures.

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SUMMARY

Shade structures are becoming very common in Australia. They have started from horticultural applications, moved into smaller domestic applications, small commercial projects such as car dealers as well as the broad acreage applications for nurseries and mass storage facilities. Structures from shadecloth would exceed, in area, the total of all other fabrics combined by a large margin. Australia is fortunate to be leading the world with shadecloth manufacturing technology.

1. A BRIEF HISTORY OF GALE AUSTRALIA

Gale Australia is the story of how a small hand-woven scarf business grew to become the world's largest manufacturer and marketer of plastic knitted textiles for outdoor use ... and the fastest growing garden and leisure products company in Australia.

In 1951, Harry and Barbara Gale established a small business manufacturing small woven and knitted scarfs for retail department stores, later expanding the range to include children's and babies clothing. During the 1970s all Australian textile manufacturers came under pressure from less expensive import from Taiwan and Hong Kong, where labour costs were substantially lower than in union prevalent Australia. At that time, Gary Gale was completing his formal textile engineering education at the Karl Mayer school in West Germany which is part of the Karl Mayer Company, the world's largest manufacturer of Raschel knitting machines.

Karl Mayer at that time began to utilize various plastic threads in its knitting technology and supplied this technology in Australia to the Gale family who developed plastic knitted shadecloth for outdoor use. Although initially sold to commercial growers of flower crops, the product was successfully expanded into retail markets through an association with Nylex Corporation and its National Marketing Manager, Graeme Pope.

In 1982 the Gale product was known as the brand *Shade Knit*. In 1986, Graeme joined the Gale Company and established the creation of a outdoor fabric division. Later, a North American operation provided Graeme with new technology, products and experience in the fields of Gardena watering products, Enviroshade sun protection structures and Planterra ranges of decorator containers.

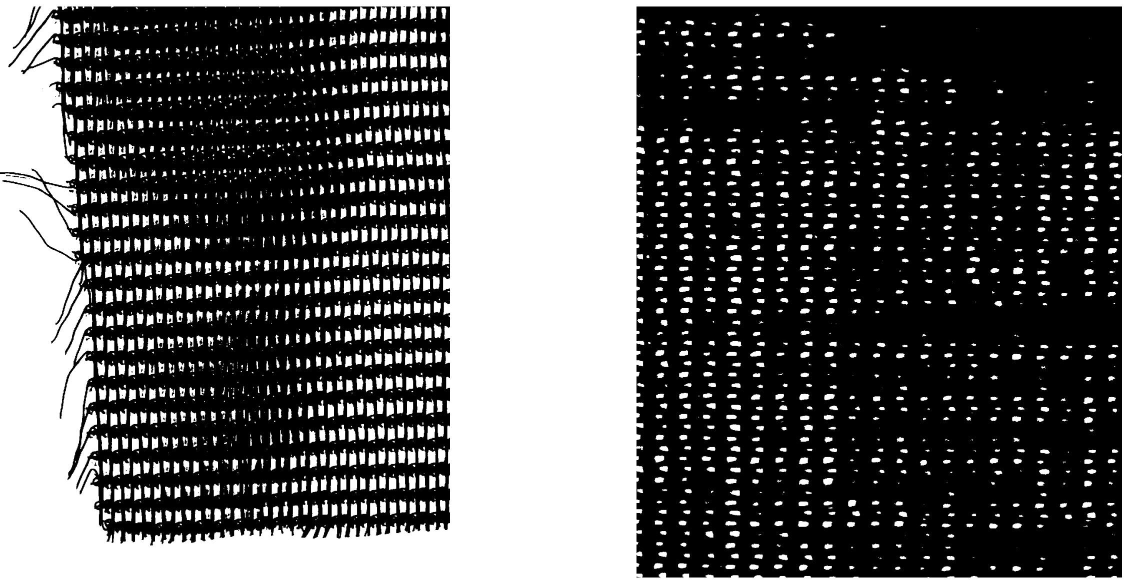
As the knitted shadecloth technology has displaced the woven form, Gale Australia has expanded its fabrication division and recently created a fabric structures division known as Oasis Tension Structures.

2. KNITTED SHADECLOTH FOR LIGHTWEIGHT STRUCTURES

The main product range used for lightweight structures is **Weathashade**. Weathashade comes in a variety of forms all utilizing knitted polyethylene monofilament/tape shadecloth using twin stitch lock knit construction.

It is normally supplied in 50m rolls in widths of 1830mm (6') or 3660mm (12') in colours – green, black, white as well as toffee, sandstone, sea green, ice blue and peach. Special runs may be produced with stripes to suit company colours or applications such as safety barriers.

Which particular *density* is defined by industry accepted *shade factors*. Common factors are 50%, 70%, 80% and more recently 90% shade factors are possible.



Knitted Shade Cloth (70% shade factor)

2.1. Product Features

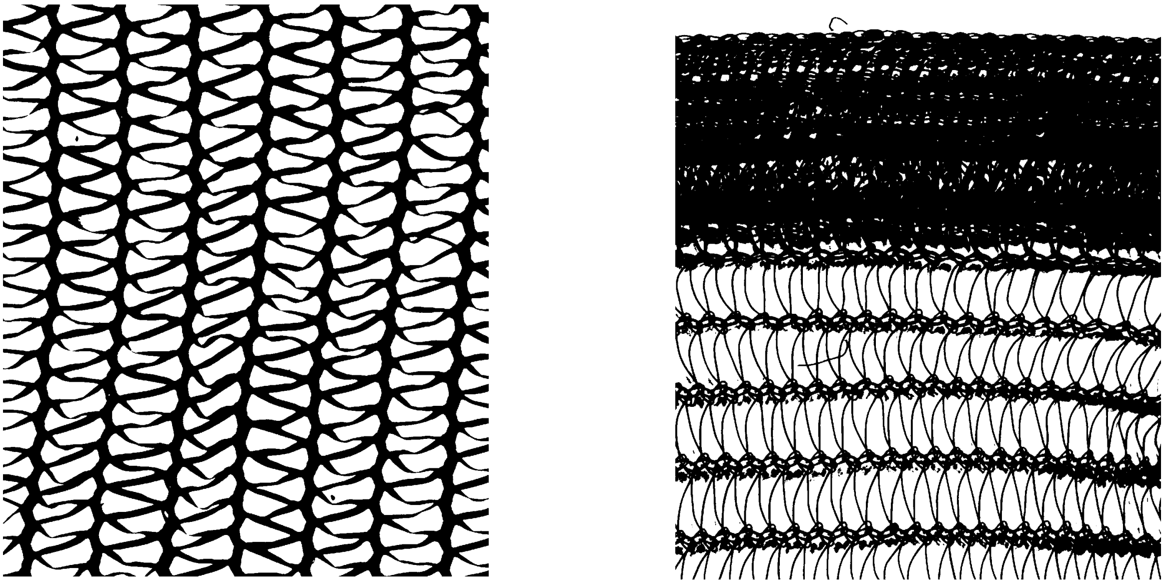
Some product features are:

Monolon Monofilament	results in low shrinkage shadecloth with high tensile strength and UV stabilization – designed for prolonged outdoor exposure.
Twin Stitch Lock Knit	Thousands of knitted springs lock together in a unique twin stitch construction giving the fabric its extension characteristics.
Ultra Violet Stabilization	The UV inhibitors are the most expensive polymeric amine light stabilisers developed and supplied by Ciba Geigy Australia.
Shrinkage	All plastics shrink under prolonged outdoor exposure. Weathashade shrinks less than other brands.
Chemical Resistance	Unaffected by normal horticultural chemicals. Will not rot and resists mildew.
Tear Resistance	In independent NATA tests, knitted Weathashade (Premium) gave 15 times the tear resistance of leading woven shadecloths and does not fray easily when cut.

Rain Misting	Knitted fabric offers superior misting of rain due to its three dimensional surface.
Reinforced Edge	Weathashade incorporates a new strong reinforced edge offering 20% more tear strength.
Fixing Accessories	A range of fixing accessories has been designed for use.
White Shadecloth	For nursery applications, white knitted shadecloth results in an increased growth rate and earlier flowering, improved plant shapes and colours, buds last longer and there is reduced fungal growth. The white colour reflects more heat on hot days and deflects interior heat on colder days giving high frost resistance.
Hail Resistance	Very resistant to large hail stones – unburstable at 50kg force (ASTM–D261–62)
Early Fire Hazard	Test AS1530.3.1982 gave Spread of Flame Index 0

2.2. Knitted Hail Mesh

The following diagram illustrates a much more open mesh primarily used for hail protection as distinct from providing shade. On the left, the sample uses a flat thin tape whereas the right hand sample uses the monofilament but with a reinforced edge strip enabling adjacent rolls to be joined by sewing.

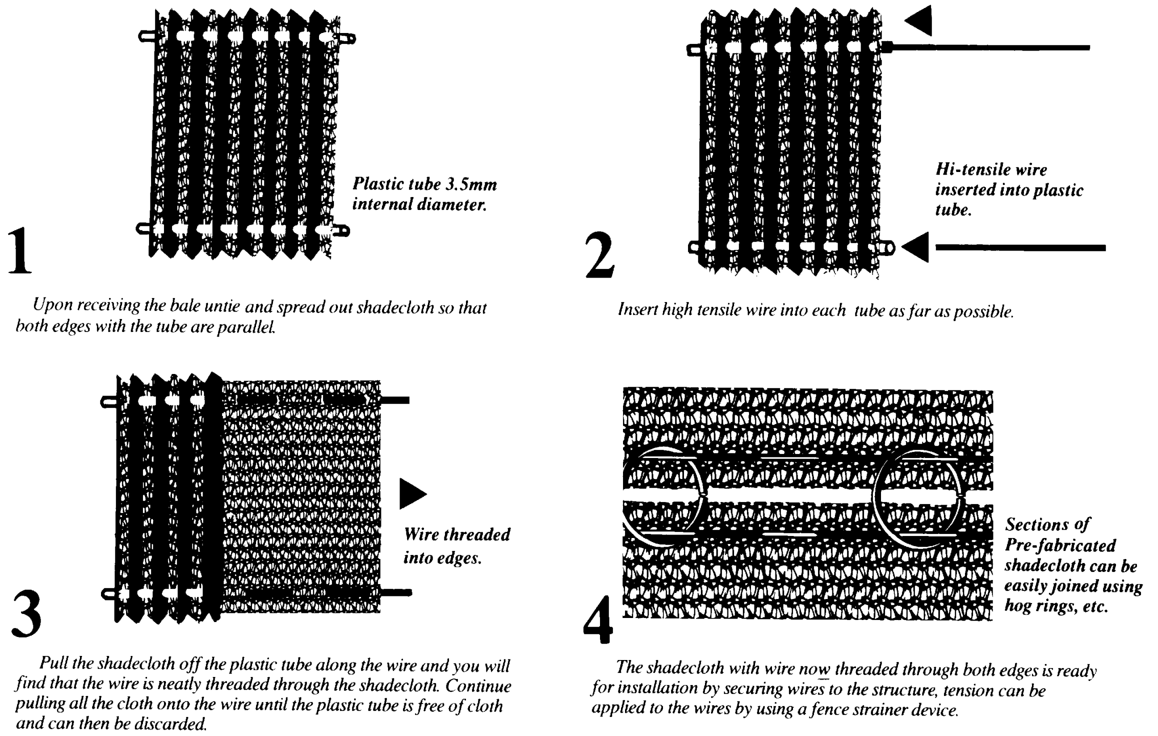


Examples of Knitted Hail Mesh using Tape or Monofilament with a Reinforced Edge

2.3. Special Applications

These can be accommodated with carefully designed cloths. One example is the safety barriers with its approved colours.

Another application is the ***Pre–Fabricated Shadecloth***. This is a unique process developed by Gale Australia which makes installation in some applications very simple. After the shadecloth has been knitted, it is fed through a special machine which threads a 3.5mm ID plastic tube of 2.5m length through both edges of the shadecloth, about 15–20mm in from the edge. The threading process creates a gathered effect, similar to a curtain, resulting in 50m being gathered down to 2.5m approximately. On the job, Hi-tensile wire is inserted into the plastic tubes and the the cloth is pulled off the tube which is then discarded. See the following diagram.



Pre–Fabricated Shadecloth

2.4. Product Applications

Knitted shadecloth finds widespread use in horticulture where it provides an environment protection from winds, severe sunlight, frost, heavy rain, dust and hail. Different degrees of protection can be provided depending on the local climate and the crop grown. It goes without saying that adequate natural light still penetrates for healthy plant growth. Drastic temperature fluctuations are smoothed out.

Domestic applications include covering pergolas, shadehouses, verandah awnings, ferneries, fence and pool privacy screens, wind protection and carports.

Commercial applications include hail protection for cars in dealers yards and new car storage facilities. Virtually every car dealership yard with outdoor storage now has some form of shadecloth structure primarily because of increased insurance premiums (or not being insurable) for hail damage.

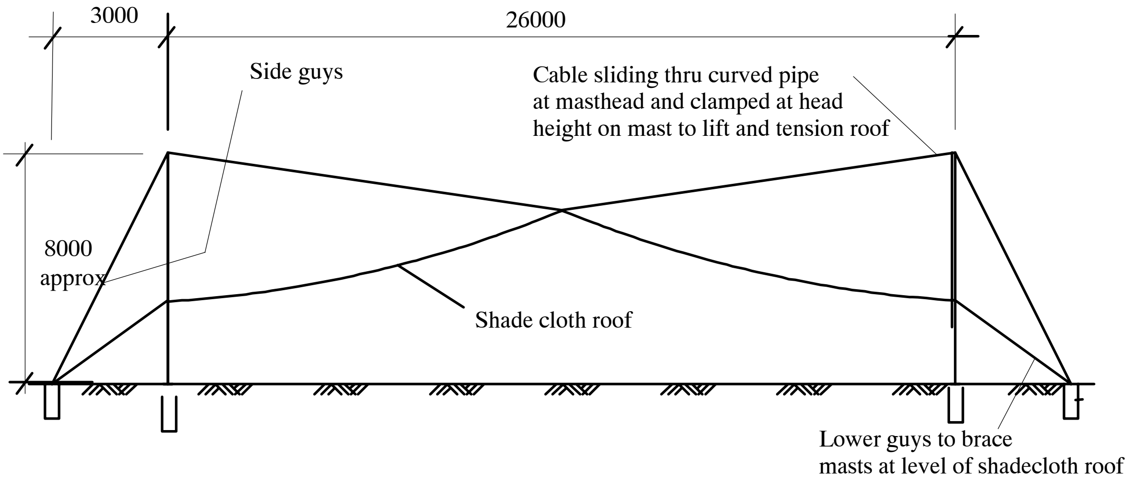
Small shadecloth structures which consist of crossing curved pipe arches between four corner posts are ideal for many regular sites whilst panels attached to overhead cables between perimeter columns are common for irregular sites.

3. DESIGN OF SHADE STRUCTURES

From an engineering position, the factors to be considered are:

Deflections	Shadecloth is extremely flexible. Panels of 10m span may well deflect 1–2 metres under strong winds and up to 3–4 metres under a heavy hail load.
Loadings	Exact environmental loadings are best described as unknown. There is little consistency in the industry as to the importance of a shade structure, hence the design return period and so on. The permeability and flexibility of the cloth alters the wind pressure coefficients. There is some evidence that for flat, taut panels in a roof, the action is to develop travelling waves across the roof with overall uplift forces considerably less than for a static impermeable surface.
Connections	Many early failures in shade structures were due to tearing of woven shade cloth at the connections. Often connections were wire clips or isolated nails through battens onto timber rafters. Many acres of torn shade cloth resulted. The most successful applications have developed from knitted shadecloth panels invented by the author with continuously sewn edge seat belt webbing terminating in more conventional shackles at guyed posts.
Prestressing	Because of the large deflections, it is necessary to evenly prestress the shade cloth so that whipping and flapping is reduced. Prestress levels are much less than coated fabric structures and typically should be in the range 0.2 to 0.4 kN/m.

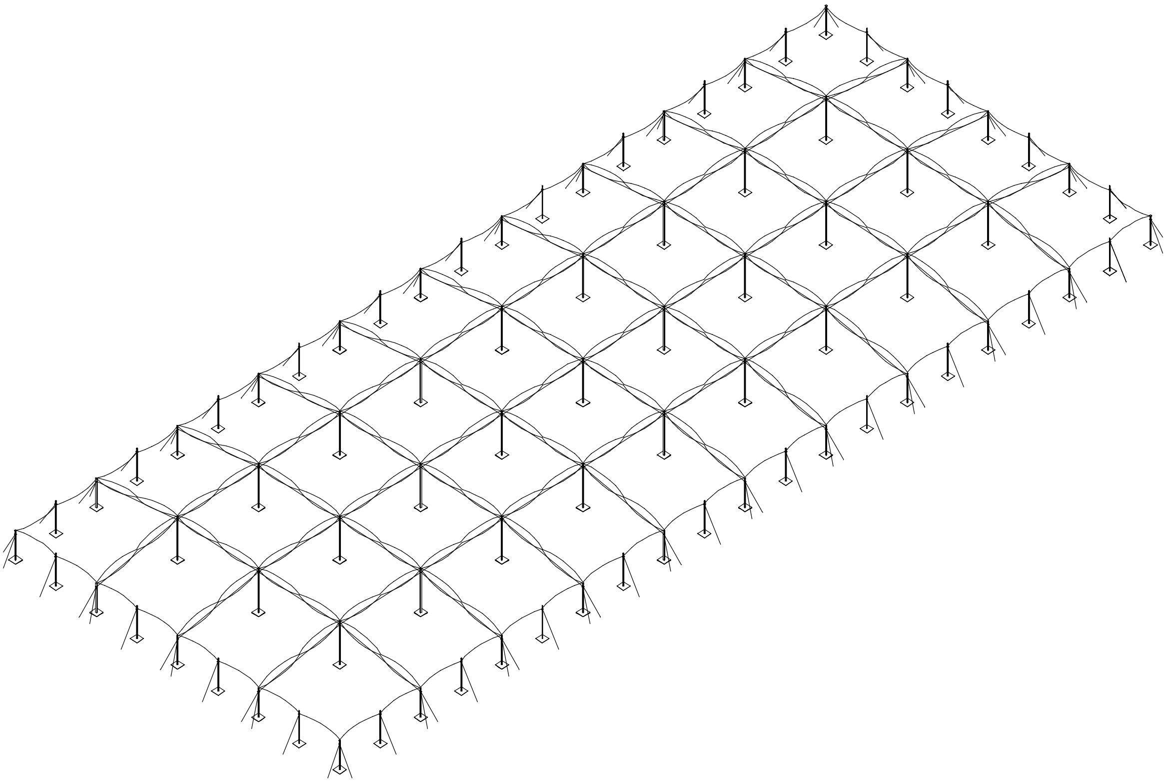
3.1. A Cable Supported Design



Concept Drawing of a Single Span Cable Supported Shade Structure

3.2. LARGE MODULAR SHADE STRUCTURES

A large number of nursery and car storage structures have been built in Australia and overseas based on modular panels approximately 14 metres square using knitted shadecloth sewn to catenary edge webbing and attached to isolated steel columns. A typical size is shown below.



The main features of the ***Oasis*** Modular Shade Structures include the now accepted standard features of modular construction – the use of knitted, UV stabilized shade cloth, continuous sewn attachment to webbing which transfers the loads to external and internal columns.

The new design however incorporates significant changes and improvements over the original concept developed by the writer in the early 1980s. Briefly, the main ones are:

- Panels to be individually attached to tops of columns
- The use of additional mid–side, inter panel connections which effectively halve the spans of the webbing
- Revised corner attachment details to significantly reduce tendency of the webbing to twist and be cut by the conventional D rings
- Use of internal cables below the level of the roof panels to restrict the build up of damaging deflections and whiplash in the overall structure under storm conditions

The first and third of these leads to a different top cap design which permits individual panels to be removed or replaced without the need to put the complete structure out of action (eg remove all cars whilst repairs etc are carried out).

The second major change results in a reduction in the webbing force of approximately 50% which reduces the load to be carried by any splice or join in the webbing. The strength of the webbing, especially at the internal columns is the weak link in the traditional modular structures.

The revised panel corner details attach each side webbing *individually* to a shackle. This means that if there are differences in webbing forces in adjacent sides of a panel the tendency of the webbing to move over the D rings is eliminated. This slipping and moving of the webbing has been the cause of webbings cutting through at D rings. There is no doubt that there is this movement happening under sustained wind loads, especially for large structures when sideways deflections are permitted to build up.

In addition to this *individual* attachment of the edge webbing, the actual joining of the webbing is done completely differently utilizing a separate loop of webbing which then gives *two* planes of thread to carry the load instead on one. The resulting strength of the join has been shown by repeated tests to improve the capacity by approximately 40%. The structure design has also *reduced* the force in the webbing by some 50% so the combination of features has resulted in very large increases in the factor of safety for the webbing.

The inclusion of internal cables is for two main reasons. Firstly, should any part of a large structure be damaged, this damage is expected to be restricted to that area. Without these cables, any failed region will mean that **all** internal columns and panels will move about in an uncontrolled fashion causing whiplash in the panels, uneven tensions in the webbings leading to cutting of the continuous webbing on D rings and potential direct damage caused by the moving columns themselves.

The second reason for the cables is also mainly directed at the larger structures. Under sustained wind from one direction, the roof must deflect sideways with the result that the leeward panels will undergo whiplash and lead to damage in the manner described above. The internal cables are there to *control* this sideways deflection with the result that, in storm conditions, all roof panels should remain taut and escape serious damage caused by whiplash effects.

4. FAILURE MECHANISMS

4.1. Under Wind of Webbing Panelled Shade Structures.

The primary cause of failure is known to be sustained strong winds buffeting the structure for many hours.

The result of this was that the panels on the leeward side become slacker and permit more deflections to occur. These deflections build up and impose shock loadings on all fittings. The whipping action of these leeward panels lead to some movements of the steel D rings at the corners which eventually cause the D rings to cut through the perimeter webbing.

Once a corner attachment of a roof panel to a pole had parted, the roof around this region would be slacker and hence whip to an even larger extent. This would cause further failures of other panel corner attachments and eventually a pole could part company from the roof.

The subsequent violent flapping in the now slacker areas lead also to regions where the shade cloth torn away from the perimeter webbing, or tears developed in the infill regions between adjacent roof panels.

Prior to, or following a failure at one or more D rings, the top of an internal column in a loosened area could be expected to oscillate quite widely causing distress to the base attachment detail as well as the top caps.

It is very apparent that the internal field splices restrict the spreading of a failure to within a region defined by the field splices.

4.2. Addressing These Weaknesses

- Provision of wire rope guys directly between columns to prevent the build up of horizontal deflections which in turn reduce large areas becoming slack and flapping violently causing shock loadings in all components but in particular the D ring type of fitting at the corners of the panels.

- The decreased buildup of horizontal deflections due to the provision of the above mentioned guys will reduce the vertical deflections under wind loads as the leeward panels would remain tauter. This in turn reduces the horizontal loading due to decreased projected areas of fabric exposed to the wind.
- Ensure that adequate numbers of ”field splices” with their extra guys are used for large structures so as to:
  a) reduce the buildup of horizontal deflections due to wind,
  b) confine any major damage to parts of the structure
- Employ corner fittings that permit large variations in webbing forces in adjacent sides of the panels without forcing relative movements of the webbing and fittings leading to cutting actions.

4.3. Failure Mechanisms Under Hail Loading

Hail loading for shade structures is generated by the hail collecting on the roof, causing large deflections which in turn cause the hail to accumulate in the natural low points in each panel. This deflection and accumulation happens quickly preventing any possible shedding of the hail over perimeter edge cables or webbing. Even inclined roof panels are not expected to shed the hail loading.

Once the accumulation has taken place, the melting process can be very slow and extend for many hours or even days.

Under hail loadings, the main causes of ”failure” are:

- sustained long term high stresses in the fabric and also any attachments of fabric to supporting cables or webbing.
- the generated forces in the supporting elements (cables, webbings) cause direct failure. Where cables are joined or terminate at a mast or anchorage, the use of less than the required number of clamps would permit slippage and hence failure even though the strength of the wire rope had not been exceeded. Similarly, the strength of the webbing would effectively be related to the strength of any sewn joins (about 60% of the webbing strength for most existing systems).
- the collapse of any supporting compression member due to the buildup of the hail. The capacity of a column is inversely related to the **square** of the slenderness ratio. ie

  Capacity is proportional to $1 / (\text{length x diameter})^2$

  Hence tall, small diameter pipes are extremely weak.
- the end user of the structure should expect very large deflections of the shade cloth to the extent that sizeable masses of collected hail might nearly reach the ground, or come in contact with stored cars. This might cause some damage to paintwork.

4.4. Addressing the Hail Loading Problems

- Use a netting with a very low shade factor so as not to collect the hail – this would offer virtually no other protection and is regarded as not a viable solution.
- ensure columns are of adequate size to carry the accumulated loads
- use shade cloth to cable/webbing attachments which are continuous rather than isolated stress concentrations (eg avoid the use of wire loops at even 100mm centres)
- avoid the use of plain woven fabrics and use knitted fabrics to have a better resistance to tear propagation.
- have structures where the roof panels are taut to start with so that for smaller hail storms, the deflections under accumulated hail are smaller.
- reduce the forces in the edge webbings by having smaller edge catenaries.
- ensure any wire rope clamps on edge cables (if used) can develop the required strength.
- employ some hail relief mechanism (the rest of the design should not rely on its operation as far as the design forces are concerned however).
- if isolated panels fail, then to have a means to keep the remaining structure standing in essentially the same position by a system of independent cables to the masts.

In regard to the reduction of forces in the edge webbings, there are two basic common suitable webbings available with strengths of about 20kN and 44kN. The forces in the webbing are approximately given by:

$$\text{Force} = w \cdot \text{span}^2 / (8 \cdot \text{sag})$$

where w is the tension in the shade cloth panel, the sag is the amount of curve.

Thus, for a 7.2m span with an edge webbing sag of 0.6m would have a tension of approximately 45% compared to a 14.3m span and a sag of 1m under the same shade cloth tension. If the same heavier webbing is used, then the strength of the shade cloth panel under hail loading can be significantly improved.

For internal edges, simply joining the mid points of adjacent panels will help but for the edges, either an additional smaller column is needed or some suspension to a strong edge cable – the extra edge column be preferable.

5. FREEFORM SHADECLOTH STRUCTURES

Several designs for freeform surfaces have been carried out in conjunction with the **Fabdes** computer program. The basic aim of these designs is to utilize the extension characteristics of the cloth to eliminate the use of cutting patterns except on the external perimeter.

This surface was generated along the following steps:

1. To generate a flat 4 sided region at the height of the perimeter columns. The mesh size was selected to be square in both directions and, for this stage

was 1m in each direction. The number of divisions was 20x46. Only the edge lines were generated in this step.

2. Line elements were generated around a rectangular opening at one mast position and then copied to the other two masts. The size of the opening was 4 meshes across the shorter dimension and 2 along the long dimension. From the mid–side of the opening, two lines were added to the central node which later will have its coordinates changed to represent to top of the mast. This hole was later created by eliminating the elements connected to the internal nodes using the **node–del** command.

3. The mast top locations, currently in the same horizontal plane were raised to the 11 metre level.

4. The surface was smoothed out. The corner points and side mast points were fixed in position, as was the top of the masts now set at the full 11 metre height. Lines to the mast top were given a heavier weighting of 10, the lines around the eyes a weighting of 4 and the edge lines a weighting of 8. This was the outcome of one or two trial runs.