

## FABRIC TENSION STRUCTURES: CASE STUDIES IN NEW ZEALAND FROM AN ENGINEERING PERSPECTIVE

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### Abstract

Fabric tension structures provide a very flexible medium for design. They give the architect an opportunity to explore a wide variety of shapes and form not achievable with more traditional materials. Their economy of structure and speed of erection make them appealing.

This type of structure does however require an understanding of the relationship between curvature, tension and deflection in order to produce a satisfactory design. An understanding of load paths and attention to detail is important as the support structure is usually exposed. Fabric tension structures make an intriguing case study as a group because although they are all based on the same principles, a vast number of variations on shape can be achieved. It requires research and experience to identify which shapes work well and which shapes physically cannot be achieved or are not ideal in their performance.

Deflections of fabric tension structures are larger than those of traditional structures. This produces the need for non-linear analysis methods to check the performance of shapes and achieve accurate estimates of the forces in the structure.

Here we will provide case studies of three fabric tension structures that have been recently investigated. Each of these structures has very different objectives and constraints governing their design. We will review how these objectives were achieved, and some interesting design issues that arose during the course of the projects.

APEC Signage - The 'APEC Sails' consist of two 20m high structures supporting signage for the 1999 APEC Conference in Auckland. Fabric was used to emulate boat sails on either side of a mast. Getting an accurate understanding of the shape of the fabric, it's 3 dimensional appearance, it's fit amongst struts and cables, and ensuring the short production deadline was met were the most important features of this job.

Waikato Stadium - We looked at providing an alternative to iron roofing for the stadium. Although the architect preferred fabric, it was important to achieve a solution that was in the same price range as the metal cladding.

Deloitte House Rooftop Canopy - A canopy was built on the rooftop of Deloitte House to provide an area for entertaining that overlooked the harbour. Site restrictions, including maximum heights and keeping structural forces low for connection into the existing structure, needed to be achieved. These requirements ended up controlling the structural form.

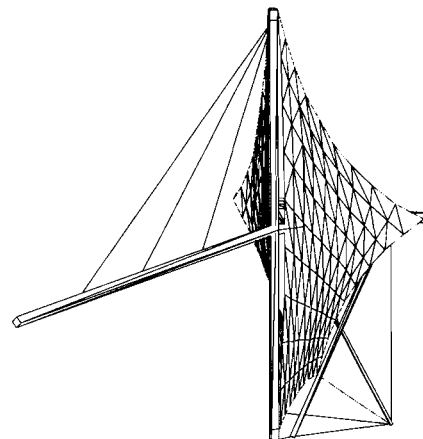
### Case Study One: - APEC Signage

The 'Apec Sails' consist of two 20m high structures supporting signage that cantilevers over four lanes of motorway. Fabric was used to emulate boat sails on either side of a mast.

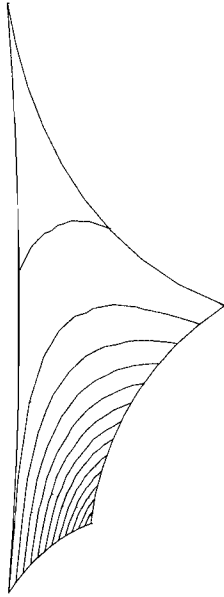
The signage was initially designed for the APEC Conference in Auckland last year. It was initiated in the late stages of conference planning and due to the association with Auckland International Airport it required the co-ordination of a large number of different consultants. Timing was paramount - the project had to be complete before the APEC conference. Each discipline was given a schedule that provided very little leeway to complete their portion of work.

Fabric analysis was carried out early during the concept stages of this project. It provided a good starting point for the work by accurately establishing a feasible sail shape and associated loads in the support structure.

A step by step process was used in conjunction with 3-d drawings of the structure to develop a clearly defined fabric shape satisfactory to the architect (ref. figure 1). This ensured that the architect had a clear understanding of how the sails would look in any direction.



**Figure 1: 3-D :Model of the APEC Sails and Support structure**



**Figure 2: Contour Plot of the Fabric Sail**

The aim was to maximise the signage area while maintaining enough curvature in the fabric to control deflections. Similarly, cables were required to be as straight as possible without producing excessive loads on the support structure. By adjusting cable tensions, fabric pretension forces, and support positions an acceptable solution was developed. Contour plots of the fabric shape further clarified the amount of curvature in the fabric (ref. figure 2).

The 3-drawings also highlighted potential clashes between the fabric and the complicated support structure. This information was invaluable in getting the fabric dimensions, cable tensions, and support locations right first time, thus ensuring that this project ran smoothly given the strict time constraints.

#### **Case Study Two: - Waikato Stadium**

A proposal was made to upgrade the Hamilton rugby grounds into a Stadium for Rugby and Cricket. Part of the proposal involved providing a roof over the new seated portion of the stadium.

There is a common misconception that all fabric structures are by nature inexpensive. For traditional structural forms fabric is often not the cheapest material. Fabric has no compression or bending strength. Consequently the support structure is required to be stronger to support the fabric. Fabric has many other valuable features which make the expense worthwhile, for example improved light transmission, good thermal and acoustic properties, however it becomes competitive price wise when curved and interesting shapes are required. Fabric is also cheaper when large spans require covering. The ability of fabric to span large distances is the attribute that made it competitive for the Waikato stadium.

Unfortunately fabric was not investigated at an early stage in the design of the Waikato Stadium. Cantilevered frames were designed to support iron roofing. The maximum purlin span that could be achieved with iron was 9m. Thus the cantilevered frames were spaced at a maximum of 9m apart. This spacing did not allow the frames to be neatly positioned in the seating aisles.

If fabric had been investigated at an earlier stage it would have emerged that the frames could have been spaced further apart requiring less frames and achieving a more aesthetically pleasing result.

The fabric was required to be relatively flat for the Waikato Stadium Roof. This posed problems because when loaded a flat panel will deflect more than a curved panel. The designer needs to be very careful that ponding will not occur. Once ponding is initiated in fabric the deflections increase and the cover can easily tear itself apart trying to contain the water. This problem was reduced by using a relatively high prestress force radially through the fabric. Because of the shape of the stadium most of these radial forces were self resolving.

Cables were also found to work very well along the front edge of the roof. They followed a true circle, where beams along the front would break the shape into a series of straight lines. The angle that the cables formed with the cantilevered beams meant that the compression forces normally present with tensioned structures were resolved without putting large compression loads into the cantilevered frames (ref. Figure 4).

The back of the roof already had a large beam running between cantilevered frames to horizontally brace the stadium structure. This beam had enough capacity to support the fabric as well as acting as a gutter.

The main alteration we made to the concept design that affected the price was to remove every second cantilevered frame. It was found that with additional cable bracing, the fabric could adequately span twice the distance of iron.

A basic rule of thumb for beam design is that strength is proportional to depth squared. So to double the strength of the remaining cantilevered sections we only needed to increase the depth by 40%. In this case the cantilevered section was an I-section. We found that only the depth of the web needed increasing, so steel volumes only increased marginally. This is a marked cost saving in comparison to installing another cantilevered section.

The final result was to achieve overall cost savings that allowed fabric to rival iron roofing. Unfortunately at this stage the project looks unlikely to proceed due to political issues.

### Case Study Three: - Deloitte House Rooftop Canopy

Deloitte House is a new 9 storey office block in Downtown Auckland, with views over the America's Cup village. A roof top entertaining area was designed and built to provide an outside environment that still provided protection from the elements.

The architect's vision for this structure was to use fabric over fanned arched frames. The challenge was to achieve a canopy that fitted the proposed shape, fell within height restrictions and still produced a well performing fabric cover.

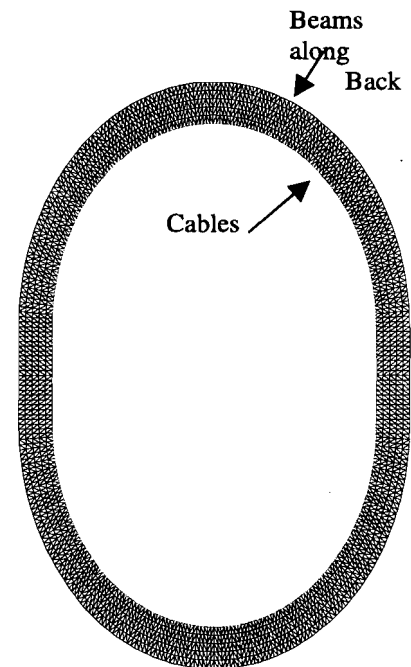


Figure 3: Fabric Layout for the Waikato Stadium

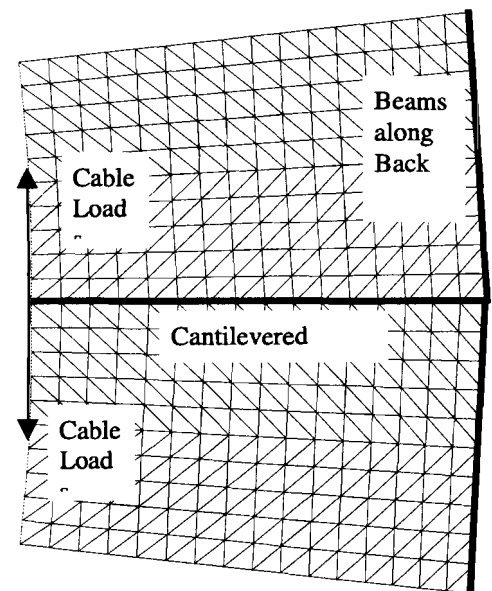


Figure 4: Angle of Cable Loads with Cantilevered Beam

What on the surface appeared to be a simple form, turned out to require a large amount of analysis work to balance form, stability, and fabric performance.

A canopy located 28 meters up a building, facing the sea has considerably larger wind loads than a canopy at ground level, thus the loads designed for in this case were considerably higher than those for a typical canopy.

The shape of the arched frames in this canopy is less than ideal from a design point of view. Within reasonable limits, more curvature in arches will improve the 'hug' of the fabric to the frames and provide better control of the forces in the frames. With this particular canopy these issues were critical. We had to carefully adjust the radius of curvature of each frame so that it would pass over an existing roof (with a varying height), pass under the height restriction, keep the tips at one end of the frames aligned, and ensure that all arches would still support the fabric. The frames ended up relatively flat and a good arching action could not be achieved. A truss was developed to keep the structure looking light-weight while providing the additional strength required.

Having a lack of symmetry produced other problems. A full 3-d model of the fabric and steel structure was required to understand the load paths that developed. Additional bracing was installed to keep the structure from skewing in the wind. This bracing was restricted by the existing structure. On one end of the canopy the supporting frame steps over an existing wall. In order to avoid clashing with this wall the bracing was terminated short into the floor.

The cables around the front and back of the structure were carefully analysed to minimise the loads on the frames while maximising the fabric coverage. Greater coverage could be provided by either increasing the length of the cantilevered frame tips, or increasing the tension in the cables (ref. figure 6). Increasing the tension in the cables reduced their curvature, providing more coverage, but increased the loads in the frames. Extending the cantilevered frame tips also increased the loads in the frames due to the lack of symmetry in the structure. A happy medium was finally reached.

Site welding was kept to a minimum, with all connections shop welded or bolted. This again proved difficult. As connections and loads into the floors were to be minimised, frame action was required to carry the horizontal loads on the structure.

Bolting arrangements were discussed in depth to provide attractive connections that would still carry bending loads. One interesting side issue of this project was the preliminary patterning carried out. Patterning not only affects the shape of the fabric, but the position and direction of seams can change the overall effect of the canopy. The direction that the fabric runs must be decided in the early stages of a project as most fabrics have different properties in their warp and weft directions. For this project the fabric was patterned in two opposite directions to compare effects (ref. figure 7).

Although this project was far more involved than originally anticipated, all team members worked closely to produce an exceptional result, on time.

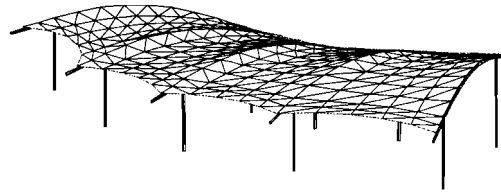


Figure 5: Deloitte House Rooftop

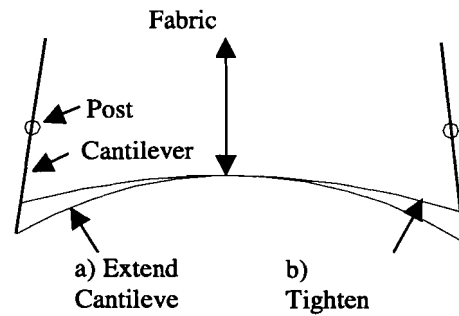


Figure 6: Alternative Ways of Achieving Fabric Coverage

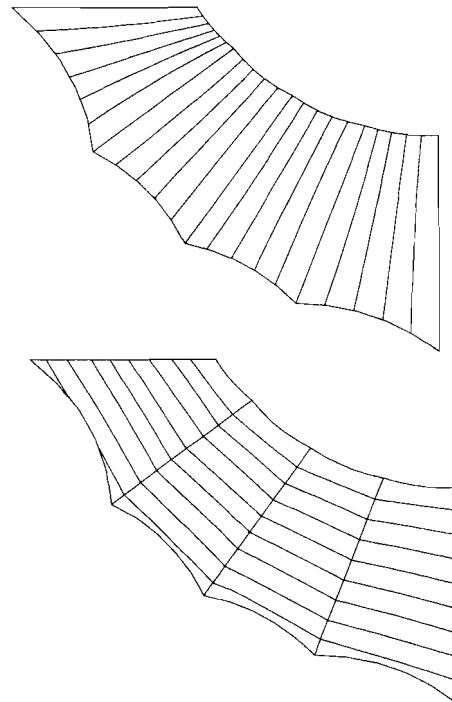


Figure 7: Plan of Fabric Comparing Alternative

**Conclusion:**

The case studies presented here describe three fabric tension structures each with individual requirements. The projects highlighted some of the design and construction issues of these structures:

Fabric shapes can be accurately developed and presented using non-linear 3-d software. This saves time and reduces the potential for error.

Fabric structures can compete on price with other materials given the right structural form, and when included in the initial planning stages of a project.

Fabric provides a flexible medium that can be used effectively in situations where site constraints are difficult.

Familiarity with this type of structure removes the risk of common mistakes being made, especially with regard to an adequate and efficient support structure. With fabric structures it is important that the analysis is carried out early in the development stages of the project. This ensures that any clashes, instability or discrepancies can be addressed at an early stage before they become expensive to rectify.