Eureka Interpretive Centre - Membrane Structure

From Concept to Icon

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Abstract

A government force consisting of detachments of British Regiments, the 12th and 40th, plus mounted and foot police of the Victoria Police, attacked an entrenchment of aggrieved gold miners at Ballarat at daybreak on 3 December 1854. The resulting action, the attack on the Eureka Stockade, is today among Australia's greatest legends.

To commemorate the events of the Eureka Stockade, a new Interpretive Centre, designed by Cox Sanderson Ness Architects, has been constructed in Ballarat. A key element of the design is the tension structure which features the Eureka Flag and floats majestically above the display buildings below. The mast of the fabric structure is over 50 metres high, with the fabric of the “flag” varying from in width from 4 metres to 12 metres.

Delivered by Spacetech under a D&C Contract, the concept and design of the mast was developed jointly by Ove Arup and Spacetech in close consultation with the Architect and their design team. This paper reviews the desig concepts and arrangements of the membrane structure and the erection method used to deliver what has become a new icon for the City of Ballarat.

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1. Introduction and Project Brief

To commemorate the events of the Eureka Stockade, the city of Ballarat commissioned Cox Sanderson Ness as the design Architects for a new interpretive centre.

The total project value of $6.5 million included a tension structure 52 metres high, emblazoned with the cross and stars of the Eureka Flag. Delivered under a D&C Contract by the nominated sub-contractor Spacetech, the design and erection method was developed jointly by Ove Arup and Partners and Spacetech.

The design, fabrication and erection programmes were critically linked to the progress of building works on site as a result of the structure's mast piercing the building envelope. Erection of the mast was to be completed within a one month window to ensure that building progress was not delayed.

Commissioned in December 1996, the detailed design and steel detailing were completed in January 1997 and the steel was fabricated and brought to site in June 1997. Prior to erection of the mast the site was made ready with the completion of the anchor blocks and footings, together with the temporary support platforms. Final erection was completed in July 1997.

To deliver the project under the time and cost constraints imposed, Arup and Spacetech had to work in close collaboration, quickly developing a vibrant, cooperative and productive environment. The majestic result is evidence of the positive team working between all team members involved.

The structure is the successful realisation of an architectural and engineering symbol - a true icon.

2. Conceptual Design

The membrane structure for the Eureka Centre is a clear example of an elegant and expressive structural form. This form is responsive to the nature of the membrane shape and the forces both acting on and through the structure. The basic form of the membrane is that of a sail. This form is very effective in the entrapment of moving air, and the forces developed naturally generate a tensile structural system as that adopted for the mast.

At approximately 50 metres high, the structure attracts considerable wind loads. The stability of the membrane itself is integral to the behaviour and resolution of forces in the cable stayed mast. The membrane is approximately 12 metres wide at its base and narrows to 6 metres at its highest point. Refer Figure 1.

The fabric is supported directly on three curved rib trusses and is connected to catenary edge cables along its 'free' edge. The tubular mast is the primary axial-load carrying strut and is stabilised by stay cables at its tip and mid-height. The membrane is attached to the front stay cables via the rib trusses and tied back to the mast at the upper levels and directly to the ground at the lower rib level.

The curvature induced in the front stay cables, generates a geometrical form that inherently maintains large tensile forces in the stay cables. This forces the membrane away from the tubular mast and thus necessitates tension ties to anchor the fabric at the rib locations back to the mast and likewise to the ground. Under all loading conditions, the stay cables hold the membrane away from the column and as a result no struts are required to connect the rib trusses back to the mast.

Primary stay cables around the mast are arranged to resist lateral and transverse wind loads. These cables also provide critical restraint to the mast, to reduce its effective unsupported length.

As conceived by the Architects, the fabric was to be stretched flat between end supports. However, the overall dimensions of the fabric generates a large surface area and hence load. To ensure that the fabric maintains its form under all loading conditions, the rib trusses have been curved and catenary edge cables included to support the free edge of the fabric. An intermediate rib truss is included at approximately mid-height, such that the span between the end restraints for the fabric is reduced and hence the induced fabric tension is lowered.

3. Detailed Design and Analysis

Loading

The dominant loads on the mast and the fabric are the initial prestress and characteristic wind. The prestress level in the cables was selected to ensure that all cables remain taut throughout all load variations, that maybe expected to act on the structure.

Wind

The wind loading was determined directly from AS1170 Part 2. The town of Ballarat is approximately 400km north-west of Melbourne. The terrain is generally flat and due to the type and density of the surrounding buildings, little to no benefit is gained from shielding against wind.

Wind forces were applied as uniform pressures derived from wind acting in the longitudinal (N-S), transverse (E-W) and diagonal directions. Non-uniform loading of the fabric surface was considered by including anti-symmetric pressures across the fabric width. This loading pattern induces global torsion or twist along the fabric length.

Prestress

Prestress levels were determined by ensuring that all cables remain taut under all characteristic load conditions. The cable prestress was maintained to approximately 10% of the minimum breaking force of the cable. By limiting the initial prestress load, tension levels in the individual cables could be adjusted by rigging screws without causing plastification of threaded elements.

Tie cables connecting the ribs to the mast have their prestress determined from the torsional load case, whereas, the main stability stays and bracing cables are obtained from overall longitudinal and transverse wind loads.

Dead Load

The self weight of the structural elements such as the mast, cables and the fabric were included in the analysis.

As the largest element in the structure, the mast is fabricated from a 610mm dia. CHS section, 9.5mm thick. Its inclination induces a natural tensile force in the front stay cables. Cable self weight can cause significant sag for large cables with long spans. The tension required to control the cable sag increases approximately with the square of the length between points of support. For the cables used, the self weight did not create adverse sag over the cable span given the pre-tensions applied.

Temperature Effects

Thermal loads induced in the cables and the steelwork were considered as a further load condition on the structure. The range between mean maximum and minimum ambient temperature in Ballarat is more severe than that in large urban cities. This temperature range considered was from a min -10°C to maximum of 60°C. The associated elongation and contraction of the cables was included when assessing the structural performance of the mast.

Foundations

The main stay cables are anchored at four locations, arranged symmetrically about the longitudinal axis. The front and back stay pairs are connected to mass concrete plinths located approximately 50 metres and 30 metres from the base of the mast, respectively. The front stays incorporate turn-buckles to allow final tension adjustment during and after erection.

The mast is supported directly onto an independent pad footing. Foundation design was by others, to whom loads were provided from the analysis of the mast.

Stability

To ensure that all acting forces are resisted efficiently by the structural system, the cable restraints are arranged to transfer all loads directly through a system of cable ties and the mast.

Longitudinal and Transverse Stability

The membrane structure is restrained from longitudinal and transverse loads by direct tie action through the anchored stay cables. The mast is effectively restrained at four points around its sectional perimeter at its tip and mid-height. A pin support is provided at the base, allowing rotational freedom for bending but restrained against torsion.

The two front stays are attached near the tip of the mast, and a further bracing tie triangulates the top connection. The top of the mast reduces in section for ease of connection detailing. This bracing tie transfers the tension forces in the front stays to the upper rib tie-back location, where the first pair of stability back stays are connected directly to the tubular mast. Further down the mast, another set of four stays connect directly to the mast from the ground anchorages. The intermediate rib truss is connected at this location on the mast.

In plan, the four stays are separated at the column connection by about 60° between the front stays and about 80° for the back stays. The symmetrical alignment and number of restraints provides direct tensile restraint to the structure under all load directions.

Torsional Stability

The asymmetric loading of the membrane over its width induces a global rotation of the fabric and hence the rib trusses. Resistance to the torsion is provided directly by the bracing and tie-back system at the uppermost rib.

The torsional brace at this level is composed of two slender struts connected to gusset plates projecting normal from the face of the mast. A column bracing tie connects to and continues beyond the end of the struts. The rib is directly tied from its ends to the mast and a further pair of ties are connected at the back of the long struts. The rotation of the rib is restrained by this triangulated system of ties and struts, transferring the torsional load into the tubular mast.

A tubular mast is very efficient in resisting torsional moments and can transfer applied torsion into the base connection. The connection of the mast to the ground is detailed as a "true-pin" along the major N-S axis but can resist moment around the orthogonal axis.

Asymmetric loads may be indirectly resisted by the front stay cables. The rotation of the membrane will develop forces normal to the cables. These forces will be resisted by the catenary action of the cables. However, since the deflection of the cables amplifies the rotation of the fabric, a direct torsional resistance system was preferred.

Mast Design

The mast is 52 metres long and weighs approximately 10 tonnes. Its structural significance is critical to the overall performance of the membrane structure.

The mast was designed to achieve the maximum slenderness possible. Therefore a number of cable restraints were attached to the mast to restrain it against buckling. The fabric is connected directly to a series of restraint ribs which are tied directly to the mast. At these locations, large concentrated cable fores act on the mast normal to its longitudinal axis. To resist such forces the mast would require a large bending capacity if cable restraints are not used, and hence could be achieved by using a deep fabricated section or a braced column.

Numerous options were explored, and the visual and cost implications of each were assessed. It was concluded that a standard tube (610mm dia. CHS) would provide the favoured solution based on the above criteria, and hence all normal forces must be resisted through a direct line of action provided by stay cables. The predominant load action in the mast is axial compression Its size is determined by the maximum slenderness achieved without buckling or failing the section. Buckling capacity of the mast was assessed for varying effective lengths and found to be optimum (when considering other criteria such as visual impact and geometrical constraints) for the restraint cable system adopted in the final solution.

The bending capacity of the section was checked under the action of its self weight during lifting and erection. It was found that a number of lifting points were required to ensure that the same section was adequate during erection or temporary works.

Cables

All cables used to stabilise the structure are galvanised steel 19-strand guying rope, G1570. Catenary cables were cut to length, such that all prestress levels would be induced in the fabric once the structure was erected. Some adjustment of the main front stay cables was provided via turn-buckles to ensure prestress levels in all other cables was achieved and maintained.

The stiffness of the cables stayed mast is directly related to the tension levels maintained in the cables throughout the loading history of the structure. To ensure that cable tensions are maintained and do not require regular re-tensioning, the prestress levels are limited to 10% of the cable breaking load. Long term cable creep was limited by maintaining tension levels under characteristic loads to about 45% of the minimum breaking load.

The fatigue loading of the structure, in particular the cables, was assessed for the appropriate wind load spectrum. The cables only undergo axial tension load cycles and do not have any full load reversal. The tension range was compare against the relevant S-N curves and since the cable stress range was significantly less than 100 MPa, and hence the cable design life is not limited by its fatigue resistance. Typically, local free bending and high tension ranges produce significant fatigue deterioration of the cables.

Fabric Design

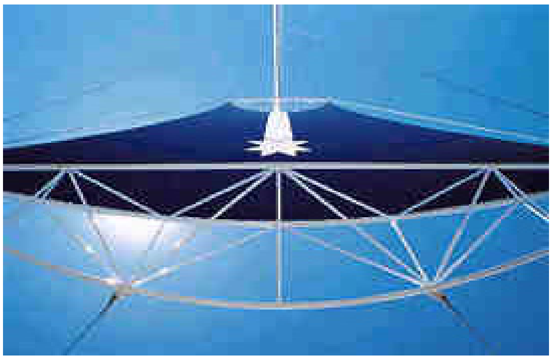
The key element of the tension structure is the fabric. The properties of the fabric were crucial to achieve an almost flat surface on which the Eureka Flag is displayed. As mentioned previously, the curvature of the front stay cables induce a stabilizing permanent tension in the fabric. The fabric curvature over its width is defined by the rib trusses and the fabric shape is maintained by catenary cables along its edge.

Under characteristic loading the maximum tension induced in the fabric is 25 kN/m. This maximum tension is localised near the intersections between the rib trusses and catenary edge cables. Under service winds the fabric deflects approximately 1200mm upwards and 1000mm down. These deflections and tensions are controlled by the pretension in the catenary cables.

Rib Trusses

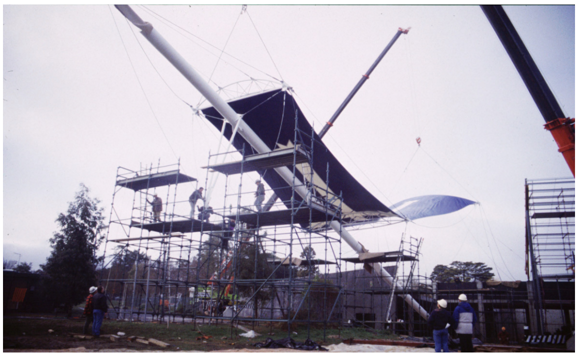
The primary function of the rib trusses is to restrain and shape the fabric membrane. The trusses also provide the primary load transfer from the fabric directly to the restraint cables and into the mast and stay cables.

The uppermost and lower trusses are approximately 4 metres and 12 metres wide, respectively. The form of the rib trusses is similar for the upper and lower trusses, with dual curved upper chords and a single straight lower cord. The upper chords are curved in plan and elevation. A reverse arrangement occurs in the central truss, where a single upper chord is curved only in elevation and two lower chords are curved only in plan.



The uppermost and lower ribs are restrained by the front stay cables at their ends and intermediate restraint cables along their length. The intermediate cables reduce the effective span of the truss in the plane of the fabric, and hence the chords and bracing members are minimised. The braces have been arranged such that they coincide directly with the intermediate restraint cables. This ensures that any bending in the elements is minimised and the braces are sized to resist concentric axial forces. The joint connections between the braces and the chords were assessed, and the members adopted do not require reinforcing within the joint to avoid local chord failure or plastification. The intermediate rib truss has the fabric connected directly to either side of the single upper chord. No in-plane longitudinal tension force is transferred from the fabric to the upper chord. The truss provides vertical support and maintains the width and curvature of the fabric.

Analysis



The entire mast structure, including the fabric, was modelled and analysed using Arup's in-house non-linear structural analysis programme (FABLON). A number of full structural models were employed to assess the effects of various stay cable positions and prestress levels. Other runs were made to determine and assess the stability and cable load effects for various lifting positions during the erection sequence. The lifting points and phasing of the erection was critically analysed to ensure that the components were not subject to significant over stress or permanent deformation. The buckling and dynamic performance of the structure (globally and locally) were considered and assessed using various computer analyses.

Structural Performance

The overall structural behaviour was assessed for characteristic and service wind speeds, 41m/s and 38m/s, respectively. The wind loads were varied for directional and local asymmetric actions acting directly on the membrane.

The overall performance of the system was critically dependant on the level of prestress, and hence, the global effective stiffness of the structure. The top of the mast and the fabric deflections were limited to about 200mm and 1000mm respectively for serviceability wind conditions. These limits were considered appropriate and internal forces and stresses were within codified and material limits.

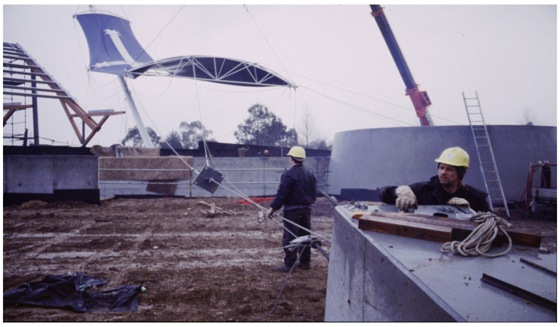
4. Temporary Works & Erection

Carefully coordinated planning was required to successfully erect the mast and associated fabric. Several scenarios were investigated and it was finally concluded that the preferred method was to rotate the fully preassembled system into place in a single coordinated process, not unlike building a ship in a bottle.

Temporary scaffold towers were erected to support each of the three rib trusses, while a special cradle was fabricated to support the mast. Connected at the base by the permanent pin, the mast was free to rotate about its north-south axis. Fabric was connected to each of the rib trusses and allowed to drape loosely between, while the rope cable stays were installed. To prevent overstress of the mast during erection, the rear cable truss was given an initial prestress.

With a close watch on the weather conditions, erection commenced in the early hours on a frosty morning in July, 1997. A pair of cranes were used to lift the upper and lower rib trusses, with tension maintained on the two front stays using hand operated cable winches. In close coordination, the top truss was raised into the air in advance of the bottom truss. Stay cables connecting from the truss to the centre and top of the mast, meant that the mast followed slowly behind the ribs as they were raised into the air.

As the mast reached an angle of 45°, the cranes held the trusses in position while two D9 excavators were connected to the front stay cables. Specially designed guide holes were left in the anchor blocks to enable tow ropes to be connected to the back of the permanent front anchor plates. Once connected, the excavators pulled forward in unison, lifting the mast, fabric and trusses into their final position. From beginning to end erection was completed in just under four hours.



5. Conclusion

As a piece of pure structure, the Eureka mast represents the success of fully integrated design. It demonstrates the vision of the architect, the art of the structural engineer and the skill of the contractor. It has provided a defining moment of Australia’s history with a physical symbol around which all can gather to reflect, contemplate and debate the meaning of Eureka to our nation.

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