LIGHTWEIGHT STRUCTURES ASSOCIATION OF AUSTRALASIA INC.

DESIGN HANDBOOK
FOR TENSIONED MEMBRANE STRUCTURES

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This document is being prepared as a basis for the structural design of tension membrane structures in Australia.

This document is issued as a “DRAFT FOR COMMENT”

Written comments may be addressed to technical@LSAA.org

Contents

Foreword / Disclaimer

1 Scope and General

1.1 Scope

This handbook sets out minimum requirements for the design, fabrication and erection of tensile membrane structures by a method compatible with limit state design codes.

This handbook applies to building structures using flexible membrane as a structural element.

This handbook is intended to apply when the membrane material is an architectural grade of one of the following:-

- knitted cloth
- woven and coated fabric
- film
- other flexible tensile material

Tension membrane structures generally employ other structural elements such as cables, beams, masts, anchors and footings. This handbook does not address the design of these other elements but where appropriate may indicate appropriate factors for use in conjunction with tensile membranes. The design of non-membrane structural elements should be done in accordance with the relevant Australian Standard.

1.2 Referenced Documents

The documents referred to in this handbook are listed in Appendix A

1.3 Definitions

For the purpose of this handbook the definitions below apply.

3D model – CAD drawing or finite element model describing three-dimensional geometry

Action – the cause of stress or deformation in a structure

Action effect or load effect – the internal force due to actions or loads

Air-inflated structure – a membrane structure with a shape that is maintained by air pressure acting within cells or tubes enclosing all or part of the occupied space

Air-supported structure – A membrane structure that encloses an occupied space and has a shape thtat is maintained by air pressure acting within the occupied space

Anchorage – a device used to secure a membrane or cable to support

Bale ring – rigid element (often circular) to which fabric is fixed, used to influence the overall shape of the membrane

Barrel Vault – membrane shape formed by fabric shaped over a series of rigid framing elements (often circular in profile and parallel)

Bias – dsadf???????????

Biaxial stress – stresses acting simultaneously in two concurrent orthogonal directions.

Cable – Tension only element (often steel wire rope) used as membrane edge element, shaping element or for connecting other elements or as stays or guys for rigid framing

Catenary – the shape (usually notionally circular) of the edge of a membrane when a cable or other tension only element is used to define the boundary. Note:- the strict definition of catenary being the shape a cable element takes up hanging under the influence of gravity alone is not often used in tension membrane structure parlance.

Catenary sag – depth of the edge catenary measured from midpoint perpendicular to a straight line between the ends.

Clamp bar, clamp plate – rigid plate (often steel or aluminium) used to clamp fabric to rigid framing element or membrane plate.

Compensation – the amount (specified as a %) by which the dimensions of a fabric cutting pattern, rope or webbing is adjusted to allow for stretch during pre-stressing. Different compensations apply in orthogonal directions for many fabrics. Determined by long term biaxial testing in the working range of the fabric in service.

Edge cable – tension only element (usually steel wire rope) used as a boundary element to define the shape of the membrane. Often in a pocket built into the edge of the membrane but can be external and clipped onto the edge of the fabric.

Edge extrusion – perimeter fixing (usually aluminium) used to secure the membrane to a rigid support

Fabric, membrane – architectural grade fabric usually comprises a woven or knitted fabric which can be coated to be permeable or impermeable. A range of different base cloth materials and coatings are available. Fabric / membrane materials are characterized by being tension only elements.

Flying Mast – rigid element usually supported by 3 or more cables and in turn usually supporting a bail ring which is connected to the fabric

Guy, Guy cable – temporary or permanent tension only element used to maintain stability of rigid elements or corner of fabric by connecting to rigid support or framing.

Geodesic – shortest path between two points over the surface of the membrane

Mast – compression element (often pinned base) used to support fabric high point often via bail ring

Membrane – fabric

Membrane plate – shaped metal plate used to clamp the corner of the fabric and connect to rigid support. Can also be used to terminate any associated edge or under or over fabric cables.

Pocket – continuous loop of fabric usually formed at the edge for insertion of a cable.

Pre-stress – tension in fabric or cable induced during installation, necessary for a stable equilibrium shape.

Rope edge, keder – incompressible rope or rod tightly secured into a loop or pocket of fabric on the edge, usually used in association with clamping bars or extrusion for fabric boundary

Seam - join in fabric

Shade cloth – open weave/ fabric usually knitted HDPE

Strut – compression only element

Swage -

Tensioned membrane structure – a structure formed by a combination of any of the following elements: structural cables, fabric or film, supporting structure which is pre-tensioned for produce a final stable form.

Top hat -

Warp -

Webbing -

Weft -

Workpoint -

Under-fabric cable -

Ridge cable -

Valley cable -

Over-fabric cable -

1.4 Notation

The following notation has been used in this handbook.

The dimensional units for length and fabric stress in all expressions and equations are taken as metres (m) and kilonewtons per metre (kN/m)

1.5 Use of Alternative Materials or Methods

1.5.1 General

This handbook shall not be interpreted so as to prevent the use of materials or methods of design or construction not specifically referred to herein provided that the general design requirements outlined in Section 3 are complied with.

1.5.2 Existing Structures

Where the strength or serviceability of an existing structure is to be evaluated, the general principles of this handbook may be applied. The actual properties of the materials in the structure should be used.

1.6 Design

1.6.1 Design Data

The following design data shall be shown on the drawings:

a) The reference number and date of applicable design Standards used.
b) The nominal loads
c) The grades of materials used
d) The corrosion protection, if applicable.

1.6.2 Design Details

The following design data shall be shown on the drawings:

a) The size and designation of each member.
b) The number size and category of bolts used in the connections.
c) The size types and categories of welds used.
d) The size, designation and capacity of fittings used, e.g. shackles and rigging screws.
e) The size of connection components.
f) The location and details of planned joints, connections and splices.
g) Any constraint on construction assumed in the design.
h) The pre-stress force for cable and fabric elements.
i) Camber of any members.
j) Any other requirements for fabrication, erection and operation.

1.7 Construction

All tensile fabric structures, designed in accordance with this Handbook, shall be constructed to ensure that all the requirements of the design, as contained in the drawings and specification are satisfied.

2 Materials

To be added

2.1 Membrane

To be added

2.2 Cables

To be added

2.3 Structural Steel

To be added

2.4 Fittings

To be added

2.5 Other materials

To be added

3 General Design Requirements

3.1 Design

3.1.1 Aim

The aim of structural design is to provide a structure which is stable, has adequate strength, is serviceable and durable, fit for purpose and which satisfies other objectives such as economy and ease of construction.

A structure is stable if it does not overturn, tilt or slide throughout its intended life.

A structure has adequate strength and is serviceable if the probabilities of structural failure and of loss of serviceability throughout its intended life are acceptably low.

A structure is durable if it withstands the expected wear and deterioration throughout its intended life without the need for undue maintenance.

3.1.2 Requirements

The structure and its component members and connections shall satisfy the design requirements for stability, strength, serviceability, brittle fracture, fatigue, fire and earthquake in accordance with the procedures given in this Standard, as appropriate.

3.2 Basis of Design

Membrane and cable structures rely on their pre-stress and geometry for structural stability and consequently may be highly non-linear in their response to load. For non-linear analysis, the following simplified rules may be considered in the case of a single predominant action:

a) When the action effect increases more than the action, the load factors should be applied to the representative value of the action.

b) When the action effect increases less than the action, load factors should be applied to the action effect of the representative value of the action.

Most cable and membrane structures are in category b). Where required by referenced design codes, limit state load effects shall be calculated by factoring the load effects with the relevant partial load factors. Whilst non-linear analysis techniques usually do not permit the super-position of load effects, for load stiffening structures, combining factored load effects is on the conservative side.

For tensile systems employing support structures which may be subject to snap-through buckling (such as slender arch supported cable nets or membranes) an ultimate load stability check should be used with a factor of 2 applied for medium or long term loads and a factor of 1.8 for gust wind loads (and in each case using appropriately stiffened material properties for any fabric membranes – unless a fully non-linear coupled analysis is undertaken to model the snap-through buckling of support systems accounting for their compliance with deforming membranes).

Other important limit state conditions to be considered are: the avoidance of progressive collapse due to the failure of any components, the assurance of the security of heavy structural components in the event of the partial failure or removal of any membrane area, and the avoidance of ponding – with the structure shaped, and remaining shaped, so that there is positive drainage from all areas.

3.2.1 Loads

The design of a structure for the stability, strength and serviceability limit states shall account for the action effects directly arising from the following loads:

(a) Dead, live, wind, snow and earthquake loads specified in AS 1170.1, AS 1170.2, AS 1170.3 and AS 1170.4.

(b) Other specific loads, as required.

3.2.2 Other actions

Any action which may significantly affect the stability, strength or serviceability of the structure, including the following, shall be taken into account:

(a) Foundation movements.
(b) Temperature changes and gradients.
(c) Axial shortening.
(d) Dynamic effects.
(e) Construction loading.

3.2.3 Design load combinations

The design load combinations for the stability, strength and serviceability limit states shall be those specified in AS 1170.0.

Prestressing forces shall be included with gravity actions in a single permanent action "G+P" and dealt with as substitute for the term "G" in all load combinations.

Ultimate wind loads may be divided by 1.5, provided that the action effects due to the wind loads are then multiplied by 1.5 for design of components.

3.3 Stability limit state

The structure as a whole (and any part of it) shall be designed to prevent instability due to overturning, uplift or sliding in accordance with the requirements of AS1170.0, AS4100, AS3600 or other relevant Australian Standard.

3.4 Strength limit state

To be added

3.5 Serviceability limit state

To be added

3.6 Durability

To be added

3.7 Fire Requirements

To be added

3.8 Other design requirements

To be added

4 Structural Analysis

4.1 Assumptions for analysis

To be added

4.2 Method of analysis

A rational method of analysis shall be used to determine the load effect on each element. All analysis and design shall consider effects of

- large deflection (geometric) non-linearity
- non-linear material properties.
- geometrical non-linear relationships of applied loads to the structure deformation.

Consideration shall be given to the effect of membrane, cable or web members attaining a state of zero tension (i.e., “going slack”). Where such condition will cause the structure to become unstable, the design must ensure that the instability will not lead to damage or collapse.

The potential for differential movement between membrane and cables shall be evaluated and where required be incorporated in the analysis.

5 Design Strength of Materials

5.1 Membrane Materials

The measured tensile strength of membrane materials is dependent on many factors including age and exposure conditions, degradation due to handling and creasing, creep and fatigue, type of stress and duration of loading, temperature and manufacturing variations. There are also uncertainties regarding loads, methods of analysis and quality of installation.

Tear strengths of fabric are also an important consideration. Small cuts and flaws in the membrane material can create conditions in which propagation under loads can lead to complete loss of a membrane panel or structure. Minimum overall factors of safety on tensile strength are adopted to provide some security against such tear propagation.

Stress concentrations can occur in membranes, particularly in corners and re-entrant edges. Fabric should be reinforced appropriately at such details.

Variations from expected stress levels can occur due to design errors and assumptions, loading assumptions, membrane patterning, other fabrication errors and installation methods. The sequence and method of installation is particularly important and should be conveyed from designer to installer as part of the design documentation.

5.1.1 Membrane Strength

The design intent is that the membrane material should retain an adequate factor of safety against applied loads throughout its intended design life. The required factor of safety SF for a structure is the product of all the partial factors listed below applicable to the project. Partial factors should be determined for the specific site and load conditions under consideration in each load case and in each principle fabric direction (warp, weft).

Minimum strip tensile strength > SF x Maximum calculated fabric stress

Where

SF = S1.S2.S3.S4.S5.S6.S7.S8 , but subject to

SF > 4.0 for permanent structures,

SF > 3.0 for temporary structures

5.1.2 Load condition factors

S1 Load factor. A base line factor of safety on loads at limit state (with prestressing forces factored by 1.5).

Use 1.5 in line with the provisions of AS1170.0

The use of 1.5 as the factor for fabric pre-stress (vs the treatment for other components of the structure) is both a simplification and recognition of the fact that fabric pre-stress may have a high variation locally, but in an overall sense will be better controlled.

S2 Size factor. This factor represents the increased risk of flaws occurring in a larger supported area than in smaller area.

Use 1.0 up to 200m2,

Use 1.2 from 1000m2 up, linear interpolation between these values.

Whilst areas in excess of 1000m2 are possible, this is a practical limit due to the difficulty in handling larger areas. The area considered here should be bounded by supports through which tears cannot propagate. This does not include cables under fabric which are not continuously clamped to the fabric.

S3 Biaxial effect factor. Uni-axial tests result in higher reported strengths than for bi-axially loaded membrane.

If the critical stress is less than twice the simultaneous transverse stress use 1.0.

If the simultaneous warp and fill stresses are within 10% use 1.2.

S4 Load Duration Factor. Fabric strength is sensitive to load duration.

Long term snow loads use 1.6, short term snow loads 1.3, wind loads 1.0.

5.1.3 Material Factors

S5 Temperature Factor. Fabric (and seam) strength is dependent on temperature with higher temperatures leading to a reduction in strength.

Most tensile test standards require control to room temperature (23degC) during testing. PVC coated membranes suffer a greater reduction in strength than PTFE coated fiberglass under elevated temperature.

Whilst wind will cause cooling of the membrane surface, it cannot be assured that all membrane areas, seams and clamp lines will be so cooled during a storm event. Factors given are for white fabric. Consider the effect of other colours and surface treatments that will absorb more heat from solar radiation.

PVC fabrics under wind and equilibrium 1.5, snow 1.0.

PTFE fabrics under wind and equilibrium 1.25, snow 1.0.

S6 Degradation Factor. Environmental exposure leads to long term loss of strength, principally from UV attack. High pollution loads can also accelerate loss of strength. The expected life of the structure should be considered in the selection of this factor. Factors should be adopted to reflect actual site conditions.

For PTFE/Glass use 1.1 for 30year life,

For PVC use 1.2 to 1.5 for 15 year life.

S7 Test Factor. Tests used as the basis for tensile strength vary in their method and reporting requirements. Different test methods have different strip widths, sample preparation and conditioning rules and rates of loading which significantly affect the reported values. Generally wider strips will result in lower tensile strengths per unit of width.

The reported values may be a mean or minimum value of a number of tests, or a result from a single test. Some makers report minimum values by choice to reflect a minimum manufacturing standard. Often this is not communicated in the product data sheets. The same fabric when tested under two different codes will achieve different tensile strengths because of these sampling, testing and reporting differences.

The designer must determine the nature of the data on which tensile strengths are to be judged.

Use 1.0 if minimums are reported and 1.15 if means are reported. In the absence of specific information use the higher figure.

S8 Material Handling Factor. Membrane material is damaged when handled during fabrication, shipping and installation. Demountable structures may be repeatedly handled. PVC/Polyester fabrics are not as susceptible to handing damage as are PTFE fabrics and greater care must be exercised during the fabrication, transport and installation of PTFE fabrics. This also accounts for some variations to design prestress that arise at installation.

Fabric Factors of Safety				
		Guide data		**Notes**
Partial factor		PTFE	PVC	
S1	Load Factor	1.5	1.5	Basic load factor from AS1170.0 section 4
S2	Size Factor	1.0 - 1.2	1.0 - 1.2	use higher value for supported areas greater than 1000m2 lower value for 200m2 or less
S3	Biaxial Effect Factor	1.0 - 1.2	1.0 - 1.2	If both warp and fill are highly stressed, choose higher value
S4	Load Duration Factor	1.0 - 1.6	1.0 - 1.6	long term snow loads use 1.6, short term 1.3, wind load 1.0

S5	Temperature factor	1.0 - 1.25	1.0 - 1.5	use higher value coupled with wind load, lower value for snow
S6	Degradation Factor	1.1	1.2 - 1.5	high pollution or high uv area use 1.5, use 1.1 with PTFE
S7	Test factor	1.0 - 1.15	1.0 - 1.15	use 1.15 if mean results are reported, 1.0 if minimums
S8	Material handling factor	1.4	1.2	for demountable structures a higher figure may be required.

5.2 Cables

(1)P For the ultimate limit state it shall be verified that $F_{Ed} / F_{Rd} < 1$

where F_{Ed} is the design value of the axial rope force

F_{Rd} is the design value of the tension resistance.

(2) The design value of the tension resistance F_{Rd} should be taken as follows:

where *F*uk is the minimum breaking force per AS2841,

*F*k is the characteristic value of the proof strength of the tension component as given in Table 6.1;

_R is the partial factor.

NOTE 1: *F*uk corresponds to the characteristic value of the ultimate tensile strength.

5.3 Structural Steel

To be added

5.4 Fittings

To be added

5.5 Other Materials

To be added

6 Connections

6.1 General

Connections shall be designed in such a manner as to adequately transfer all applied and internal forces and moments as determined by the analysis. Consideration shall also be given to any additional criteria that may impact on the performance of the membrane material and supporting structure that may not be determined from the analysis. Effects inclusive of but not limited to such as temperature, fatigue, dynamic loading or oscillations and the creep effects of the membrane material and associated connections shall be considered. Those materials not included in the scope of this standard that are used for the purposes of connecting membrane elements shall be designed in accordance with their respective codes with the loading applied as 200% the maximum stress as determined by an unfactored analysis of the structure.

6.2 Membrane Connections

Membrane connections shall be considered as those connections whereby membrane elements are attached to each other as defined by clause 6.2.1

6.2.1 Methods

Membrane seams may be considered as sewn, electromechanically welded, fused, glued or mechanically or any other means that is intended to transfer the loads from one membrane panel to another.

6.2.2 Strength

Membrane seams shall be able to permit the efficient transfer of loads as determined through analysis. Furthermore they shall be able to transfer the specified tensile strength of the membrane material when tested in accordance with the same testing procedure as listed in the technical specifications of the membrane except in the case of clause 6.2.3. The Strength of the seam shall conform to *standard*.

6.2.3 Strength Exception

Where seams have been determined to not be in accordance with 6.2.2, the tensile strength of the membrane material is to be reduced to that of the tensile strength of the seam.

6.2.4 Integrity

Any seam, by whatever means should be free of any discontinuities (such as areas of little adhesion) that will adversely affect the performance of the seam. Seams should also not significantly alter the stiffness of the membrane and allow for the anticipated elongation in the membrane under service conditions.

6.2.5 Wear Reinforcement

Where instances of wear on other structural components is likely to result in wear marks or loss of structural integrity of the membrane adequate fabric reinforcement should be used to act as a wear strip.

6.2.6 Strength Reinforcement

Where instances of stress concentrations in the membrane occur the membrane shall be reinforced as required with additional fabric.

6.2.7 Placement of Connections

Seams are to be placed in such a manner as to adequately produce a wrinkle free surface throughout the membrane and realistically reflect the analysed stress state throughout the membrane.

6.2.8 Peel and Picking

To avoid the conditions where the seam undergoes peel, the maximum angle of a welded membrane from any adjacent membrane is 12 degrees unless testing has indicated a greater angle is appropriate to transfer the required tensile strength of the membrane as defined by clause ***. Any seam or wear strip subject to potential picking is to be designed to be wide enough to ensure that no potential picking is possible.

6.3 Membrane – Non membrane Connections

Non membrane connections shall be considered as those connections whereby membrane elements are attached to other non membrane structural elements. With the exception of those clauses contained in section 6.3, all requirements contained in section 6.2 should be met.

6.3.1 Methods

Membrane connections to other non membrane structural components may be considered as bolted, eyelet, wrapped, mechanically clamped or any other means that is intended to transfer the loads from one membrane panel to other structural elements.

6.3.2 Materials

Non membrane connections should be sufficiently protected against any long term affects such as corrosion or anything else which may affect the aesthetic or structural performance of the membrane. All materials should be free of rough spots, sharp edges or any defects which may damage the membrane.

6.3.3 Deflections

To be considered later.

6.3.4 Peel

Non membrane connections can be designed in such a manner that the membrane angle is greater than 12 degrees so long as the connecting parts are adequate to transfer a minimum of 200% of the loads as determined by an unfactored analysis of the structure