The Design and Engineering of Fabric Membrane Clad Buildings

Wayne Rendely PE
132 Columbia Street, Huntington Station, New York, 11746-1220
TEL (631) 351-1843 WayneRendelyPE.com

ABSTRACT

This paper reviews the design and engineering of fabric membrane clad buildings. As these structures become more prevalent, larger and used in structures of higher importance, it is essential that engineers consider the unique forces imposed onto the structural framing by the membrane cladding.

Topics include the classification of the buildings according to building codes, code loads to be used to design the building, frame spacing, bracing and details to consider as well as the membrane forces onto the frame and how they are determined and how they affect the design of the building.

GEOMETRY

The geometry of the structure will determine the environmental loads imposed as well as the internal forces that determine the size, details, and the residual forces (opposite of reactions) imposed upon the foundations. For this paper a building using typical 2D truss frames spaced with purlins that, along with longitudinal and sway bracing, brace the frames, is considered.

- **Span:** Span is the distance between supports. and a “clearspan” would have no interior support(s). The span is a major factor in determining the magnitude of forces in the structure.
- **Ridge Height:** In a symmetrical building the center highest point of the structure. Local codes may restrict the height and wind loads increase with a higher roof.
- **Eave Height:** A consideration for internal clearances and also the magnitude of wind forces on the side wall. A higher eave may require a lower slope roof which will affect the magnitude of both the roof snow and wind loads. A larger radius will reduce clearance and reduce the magnitude of the inner chord axial force due to snow loads.
- **Roof Slope:** A low roof slope will require higher roof snow than a greater sloped roof and a high slope will need to be designed for windward roof pressure.
- **Truss Depth:** A deeper truss will lower the axial forces on the chords but the increased length of the webbing (diagonals) may affect the webbing design and size. Internal clearances, fabrication techniques and shipping may limit the depth.
- **Webbing Spacing:** Webbing members (diagonals) spaced to minimize their number will increase their size, internal forces and possibly the connection design to the chord member. Too few diagonals and upper chord local bending governs.

- **Frame Spacing:** To minimize the number of frames, foundations, purlins, fabric panels, connections and other items the frames are typically spaced as far apart as practical so as to optimize the cost. The frame spacing is a major factor in the design of the purlins. The purlins are horizontal and as compression members their self weight and slenderness will be a major factor in their design in large frame spacing. Greater frame spacing will also increase the horizontal membrane forces on the outer chord of the end frame and thus the purlins.

- **Purlin Spacing:** The spacing and design of the purlins is determined by a number of factors. Each purlin braces the truss chords and also resists the tension force in the fabric. The top chords of the end frame have fabric forces perpendicular to the truss plane and will experience out of plane bending. The purlin spacing will be a major factor in the design of the outer chord member. The purlins are also part of the longitudinal bracing system and an increase in the number of braced bays will lower the force onto the purlins.

- **Braced Bays:** (Longitudinal Bracing) Large span or tall structures will need a greater number of braced bays, bays with X-cables, so as to minimize the forces on the internal members and also the foundations.

- **End Wall Wind Posts:** These vertical tubes or trusses transfer the wind load onto the fabric directly to the ground and to the lower chord of the end frame. The horizontal force at the top of the post is transferred into the purlin, then cable bracing of the braced bays down to the frame anchors.

- **Enclosure Classification:** Internal pressure coefficients will vary based on the classification of exposure of: Open, Partially Enclosed, or Enclosed. The sum of external suction and internal pressure of a partially enclosed structure may be twice that of an open building.

![Figure 1. Define the Structure](image-url)
CODES / STANDARDS / LOADS

Most areas of the United States of America have a governing body that has adopted a “model code” and also may have adopted “amendments” or a “local code” in addition that they require be followed as to the minimum design loads that the structure must be designed for. The engineer/designer should consider higher loads if appropriate. If lower loads are to be used due to “special purpose roofs” or circumstances not considered by the codes this should be fully disclosed and agreed upon and may require a variance and approval by local officials.

- **Codes:** Determine the governing code and date of publication. This code may be the “model code” and may not give the local loads to be used in areas where local wind or snow are very site specific due to the local topography. The local code or amendments should be followed and the local building department may need to approve the loads to be used.

- **Standards:** The code will list Standards to follow for the various items to be designed in the building. Standards change and the proper date of publication should be used.

- **Loads:** Determining the proper loads will be the most important consideration in the design of the structure. There may be several correct wind and snow loads that could be used even on the same project site.

- **Wind Zone:** Most codes and standards use a map for the “Basic Wind Speed” that should be used for the design of the structure. All structures in the local area will be in the same “Wind Zone” with the same basic wind speed. This basic wind speed is typically based on the probability of that wind speed occurring over a particular period of time typically once in 50 years being standard.

- **Exposure:** The magnitude of wind pressure is affected by the surrounding terrain typically listed as: B–Suburbs, Wooded; C-Open Terrain; D–Near Open Water.

- **Importance:** The magnitude of the design loads will be based on the structures’ intended use or occupancy. The importance factors will vary depending on whether they are classified as: Temporary; Low Hazard; Standard; High Occupancy or essential.

- **Coefficients:** The actual wind or snow forces on the structure will be affected and modified based on the overall shape and slopes of the various surfaces. Wind loads will vary based on the location of the building under consideration and the direction of the wind. The snow loads include drift, unbalanced’ and rain on snow conditions. The reliance on “snow slide” is typically not allowed as there are specific roof slope coefficients that reduce the ground snow into roof snow based on roof angle, slippery surface, exposure and whether the roof is warm or cold.
ANALYSIS

Hand calculations or computer analysis of the 2-D frames should include member stiffness, end fixities, and boundary conditions. The anchors may be pinned or fixed or flexible. The connections, joints and members should be modeled as eccentric if significant or, if they are not significant, accounted for in the design process. Wind, Snow, Seismic, Thermal and other loads should be included and the end frames which have out-of-plane fabric forces should be included either in the analysis or later as part of the design. Fabric prestress should be accounted for. If the fabric can lift off the frame it may require a more sophisticated analysis model to account for the non-linear and unique “tension only” forces onto the 2-D frame which may be significant. Load cases and combinations should be created to encompass the governing conditions to design the various frame components. Analysis of the 3-D Structure for overall stability whether by hand calculation or computer analysis will indicate the forces to design the longitudinal bracing system and tension anchors.
2-D FRAME DESIGN

The 2-D frame analysis should be reviewed to determine if the results are acceptable and that the analysis model is correct.

- **Effective Length:** The design of the individual frame members will depend on the assumptions of end fixity and bracing length which will determine the effective length. The slenderness ratio of a member is based on the section properties and effective length and will be a major factor in determining its allowable compression. For the inner (lower) and outer (upper) chords the allowable compression is greatly dependant on the spacing of the purlins and sway bracing. The effective length factor will typically be 1.0 unless a rational analysis indicates that a lower (or higher) factor can (should) be used due to the influence of fixity of the webbing or the membrane attachment (or detachment).

- **End Frame Top Chord:** The fabric membrane is prestressed and also further tensioned due to wind and snow loads. The tension on the fabric will produce higher out of plane forces on the top chord of the end frame. The bending of the top chord due to the out of plane fabric forces is in addition to any axial and bending forces from the in-plane loads of the 2-D analysis.

- **Member Connections:** The connection of the webbing member to chords should be checked for local buckling.

- **Truss Connections:** The frame is composed of straight, curved and special truss sections. The truss connections should be designed for local loads thru the connection which will include the chords and webbing members and any forces due to eccentricities of the geometry of the connection and joining members.

- **Anchors:** Attachment to foundation is designed based on the 2-D analysis loads and also the additional 3-D longitudinal bracing and coordinated with, and provided to, the foundation design engineer as required.

- **Components:** Tabs and other items that may be required for purlins, braces, wind posts are designed as required.

![Figure 3. Design the Frame Members and Components](image-url)
3-D BUILDING DESIGN

The 3-D frame design is typically based on hand calculations. Some unique endwall geometry conditions may require a computer analysis model to determine the forces for design of the overall stability and longitudinal bracing system.

- **Braced Bays**: The braced bays serve several important functions: resist the wind force on the end walls; overall longitudinal stability of the structure; brace the bottom chords of the frames at the purlin connections. The braced bays should be strong enough to resist the loads but also stiff enough to be used as chord bracing. Interior braced bays are added in long buildings for stiffness and stability.

- **Tension Anchors**: Additional anchors may be required as the braced bays act as fixed end trusses and the reaction forces at the top of the wind posts are shear forces which are resisted by a moment couple at the anchors. The magnitude of the tension and compression forces of these resisting moments will depend on the spacing and number of braced bays.

- **Purlins**: The purlins are designed for the forces due to their role as axial members in the longitudinal bracing and also in resisting the tension in the fabric.

- **End support Purlins**: These purlins are designed to resist the membrane tension on the outer chord of the end frame.

- **Sway Bracing**: Either cables or rigid members that brace and support the outer chord of the frames. The strength and stiffness of the sway bracing should be sufficient to stabilize the frames in the event that the fabric suffers significant tearing.

![Building Bracing - Plan & Elevations](image)

*Figure 4. Ensure Overall Stability*
FABRIC MEMBRANE CLADDING

The fabric resists environmental loads such as wind and snow via tension only. The fabric is attached to the outer chord of the end frames, the ground (or hold down tubes between frames) and also the straight truss sections of interior frames to prevent uplift. The fabric membrane is prestressed and also further tensioned due to wind and snow loads. The tension on the fabric is determined by the magnitude of the load, the frame spacing, and the stiffness of the fabric. Higher snow, wind loads, greater spacing or stiffer fabric each produce higher tension in the fabric.

- **Prestress**: The fabric is tensioned in the warp and fill directions. A higher prestress will tend to increase longevity and enhance performance of the fabric.
- **Tensile Strength**: The strip tensile strength of the fabric is published or tested.
- **Factor of Safety**: Typical factors of safety of 8, 5, and 4 (prestress, snow and wind) are used with regard to fabric tensile strength and the tension in the fabric due to Allowable Stress Design (ASD) fabric tension. High factors of safety are used to keep the fabric stress low to help guard against tear propagation.
- **Bi-Axial Testing**: Stretch testing the fabric in two directions. The results of this test can be used to determine the stiffness of the fabric for the analysis.
- **Tension Forces**: The tension force in the fabric can be determined with hand calculations, spreadsheet, or non-linear finite element computer analysis programs.

![Figure 5. Design for Fabric Membrane Force](image-url)
**CONCLUSION**

Fabric membrane clad buildings must be designed to the same building codes and standards as conventional buildings. Additional design and engineering considerations have to be given to the fabric cladding which resists environmental loads via deflecting and with an increase of in-plane tension forces rather than thru bending like traditional claddings. The fabric tension imparts forces onto the frames unlike traditional cladding and must be accounted for. When properly designed and engineered to the appropriate local building code; manufactured and installed as per the design intent; fabric membrane clad buildings are as safe or safer than conventional metal clad buildings.

**ACKNOWLEDGEMENT**

Wayne Rendely PE – Huntington Station, New York, USA