FINAL PROJECT REPORT

Project Title: Engineering Analysis for High Density Trellis Structures

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Percentage time per crop: Apple: 100%

Total Project Request: **Year 1:** $92,500

Other funding sources: None
WTFRC Collaborative expenses: None

Budget 1
Organization Name: De Kleine Machine Company **Contract Administrator: Mark De Kleine**
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Item	**2016**
Salaries	12,000[1]
Benefits	0
Wages	71,500[2]
Benefits	0
Equipment	3000[3]
Supplies	2500[3]
Travel	3500[4]
Miscellaneous	0
Plot Fees	0
Total	92,500

Footnotes:
[1] Cost for WSU Mechanical Engineering student capstone project
[2] Wages for engineering
[3] Materials for testing and related project equipment
[4] Travel cost for meetings, orchard visits, and engineering reviews

1. Objectives

The goal for this project was to develop a standardized design practice for selecting a trellis structure based on biological and environmental factors. Specific objectives of this proposal were:

1. Perform an engineering analysis of fruit loads exerted on a trellis structure based on expected yield for high density orchard plantings.
2. Perform an engineering analysis of fixed and variable loads exerted on a superstructure.
3. Develop a trellis design tool as a planning guide for enterprise use.

2. Significant Findings:

Industry Survey Results (11 responses)

- 90% of failures were less than 10 years old and of that, 78% were less than 7 years old
- Failures in both angled and vertical systems at approximately 50-50 ratio
- In-row post spacing ranged from 40-55 feet; more than half were greater than 40 feet between posts
- Half the failures occurred in September and October with high wind events (40mph +)
- Roughly 40% were reported as anchor/anchor wire related (loose anchor, rusted anchor wires)
- 60% were reported as in-row post related (poles snapped or up ended)

Engineering Analysis

- Embedment depth can be predicted for adequate foundation
- Above ground forces need to be balanced through a trellis member to below ground forces
- A fixed base, or fully embedded trellis member, reduces the soil variability to a predictable value
- Wind loads are proportional to canopy area and porosity factor
- Wind load is the critical design variable for trellis members that are embedded correctly
- Post spacing can be determined using the Trellis Engineering Model

3. Results and Discussions

The purpose of trellis is to provide support for horticulture by balancing above ground forces (loads) to below ground forces (foundation), through a desired material (member). General trellises consist of: members, wires, and anchors. Environmental factors include wind, tree structure, fruit, and soil foundation. Trellis components act together as a system and should be considered as such.

Each trellis component has a maximum limit (load) for which permanent yielding will occur when the applied loads exceed the ultimate load. Permanent yielding is considered failure, and significant decreases in material properties occur once permanent deformation starts. The focus of this analysis is to limit members to a value below the maximum, by including factors of safety.

Above ground forces include wind, canopy, fruit, fabric, wire, and not all forces act in the same plane. For example, wind acts perpendicular to a member whereas fruit loads act axially. Wires, that are tensioned, will act perpendicular to a trellis member but not necessarily in the same direction as the wind. Therefore, a trellis member must provide adequate support in all directions.

3.1 Soils and Foundation

EMBEDDING A TRELLIS MEMBER PROPERLY IS AN IMPORTANT ASPECT OF TRELLIS INSTALLATION AND STRENGTH. IF THE MEMBER IS NOT EMBEDDED TO THE PROPER DEPTH, THE SOIL WILL BE THE LIMITING FACTOR FOR THE TRELLIS'S STRENGTH. A SOIL LIMITING STRUCTURE IS UNSTABLE IN PRACTICE AND NOT RECOMMENDED WITHOUT ADDITIONAL DESIGN CONSIDERATIONS MADE BY SOMEONE SKILLED IN THE ART.

There are two general types of trellis post configurations: constrained and non-constrained. Most WA orchards have non-constrained posts which are pounded or set into augured holes. Soil and/or restraints provide the lateral support (strength and stiffness) for a trellis member foundation. Adequately embedding a member ensures that the soil will not be the limiting factor when selecting materials. A properly embedded member is considered a 'fixed base' for engineering analysis.

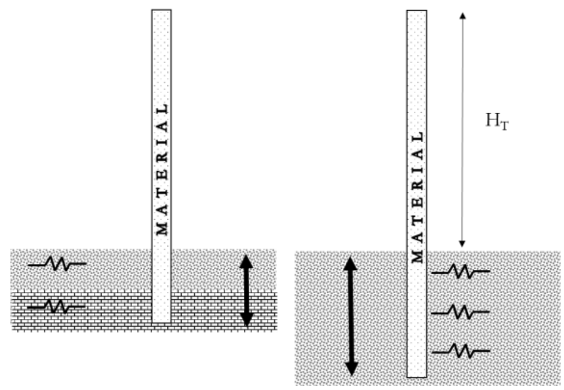

Figure 1. Layered soil (left) and uniform soil (right) represented as springs.

Embedment depth is determined from either ASABE EP486.2 [3] or ICC/IBC Soils and Foundation [4]. In general, these two references have similar outputs however when soil layers are present, ASABE EP486.2 employs more exact solutions. From ICC equations 18-1:

$$d = 0.5A \{1 + [1 + (4.36\, H_p / A)]^{1/2}\}$$

Where: $A = 2.34P/S_1b$; b = diameter of round post or footing or diagonal of square post or footing (ft), d = embedment depth (ft), H_p = distance to above ground applied load 'P' (ft), P = applied lateral force (lbf), S_1 = allowable lateral soil bearing pressure based on a depth of one-third the depth of embedment (psf). ***Note: embedment equations are for round or square vertical members. For angled trellises, increase depth by minimum of 3b**.

If shallow soils exist and become inadequate for proper embedding, restraints should be used. Restraints reduce the required depth and are used above ground, at the ground, or below ground. Embedment depth can vary by 20% for a 12ft trellis member (H_T) depending on soil type. Soil tests are recommended using standard lab tests or preferably in-situ tests. Rock layers require less depth than clays or organic silts.

Use the range values in Table 1 in-lieu of proper soil testing. Lateral pressure values may be doubled for (isolated) trellis posts, per 1806.3.4[4]. Moisture content will decrease the lateral strength for soils which hold moisture; Quincy soils typically found in Eastern Washington, have virtually no (< 25psf) lateral strength when fully saturated. ***A failure occurred in central WA when the irrigation system was on for 20 hrs consecutively (with no strong wind event).** Consider proper drainage techniques when installing trellises in soft soils. Backfilling with concrete-attached to the member-increases the effective width of the trellis member. Material properties of the backfill should be included in a geotechnical analysis.

Table 1. Soil properties as given in ASABE EP 486.1 for 5 general soil classes and estimated post embedment depth for a 4" round wood post as percent of above ground height.

Soil Class	Lateral Pressure per unit depth (lb/ft^2 *ft)	Friction Angle (deg)	Density (lb/ft^3)	Approximate Embedment depth for 4in wood post (% of H_T)
Bedrock	1200	-	-	20%
Sedimentary rock	400	-	-	30%
Sandy Gravel	200-300	32-38	90-110	37%
Sand, Clayey Sand	150-200	26-30	85-105	41%
Clay, Clayey Silt	100-130	10-15	90-120	47%

3.2 Wind Loads

Each trellis member must support a representative load within the length of a row as shown in figure 2. One extreme case resembles a solid wall, the other extreme- only wires. A practical consideration of porosity is somewhere in the middle depending on canopy and horticultural training. Consider material on the orchard floor or superstructure that could potentially get blown onto the canopy. A trellis can only hold this material if it is designed for the additional loading. ***A failure occurred when reflective fabric on the orchard floor uplifted and caught on the trellis row.**

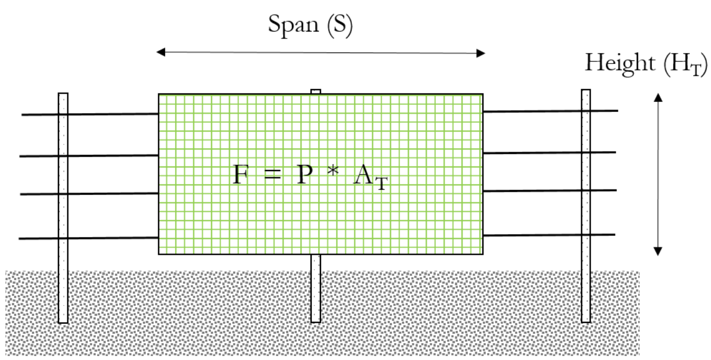

Figure 2. Example of required member support in a general vertical trellis system.

Factors included in the wind force calculation coefficient are drag, height, exposure category, importance factor, gust factor, and topography. Special cases that will affect the value of the coefficient are gorges, mountainous areas, or hurricane prone regions. MWPS-1 [1] and ASCE 7 [2] were used to develop the wind equation used for the trellis engineering model (TEM). Simply stated, and assuming a drag coefficient (C_d) of 0.5 for porous canopies, the force of the wind can be approximated by:

50% Porous Canopy	70% Porous Canopy	Solid Wall (& C_d = 1)
$F_w = 0.001 * V^2 * A_T$	$F_w = 0.0015 * V^2 * A_T$	$F_w = 0.0043 * V^2 * A_T$

Where: F_w = Force of the wind (lbf); V = Velocity (mph); A_T = Trellis Area (sqft). The trellis area is considered the span between the trellis members and the height of the trellis (top wire). For angled canopies, A_T is the projected area perpendicular to the windward direction. ***A trellis should be designed to support the actual/expected tree height and fruit region.**

When each member is embedded properly, the material can be sized based on geometric and material properties. Stated obviously, a solid wall needs more support, or decreased span, than a wall with holes. The reaction force, against the wind, of each tree was neglected as a conservative approach.

Wind force is considered uniformly distributed along the height of the trellis member (this assumption disregards any support from trellis wires and trees). Use good judgement for estimating the resolved wind force based on uniform distributed load. A triangular load distribution may be appropriate where applicable, thus changing the height of the resolved load. For angled trellis, use projected area to calculate wind loads.

A commentary on portable windbreak fences from the Saskatchewan Agriculture and Natural Resources department [7] depicts wind effects on solid and porous fences as shown in figure 4. It is important to note that both windward and leeward velocities need consideration when designing the trellis.

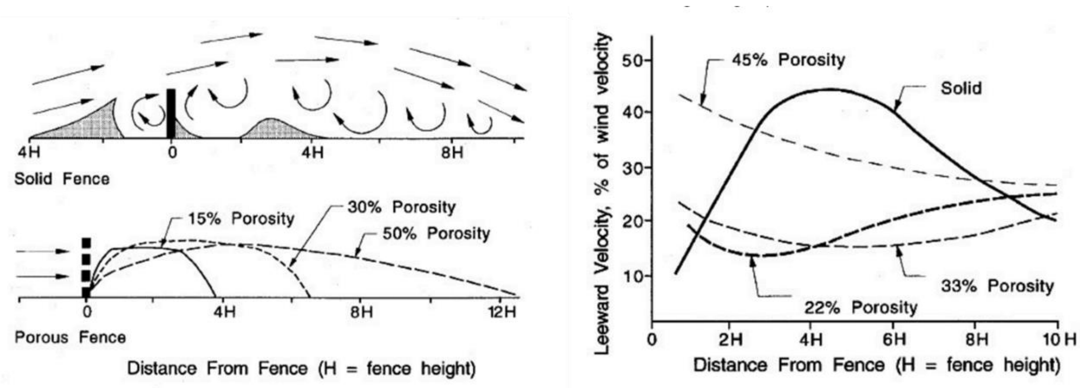

Figure 3. Wind effects shown on a solid and porous windbreak and leeward velocity representation ass percent of windward velocity.

3.3 Anchors

Anchors provide addition support to trellis members, usually used at end posts (although not restricted to end posts). Typical anchors used in WA are screw anchors which rely on depth of soil and diameter of screw to determine holding capacity. Consider weld strength when appropriate (at greater depths).

A 'frustum' volume equation can approximate the weight of the anchor system for a given soil and friction angle assuming the anchor rod is small compared to the overall volume. Use soil friction angle to determine top radius (R). Consider collars and post volumes during calculations. Refer to ASABE EP 486.1 for posts with concrete and wood collars.

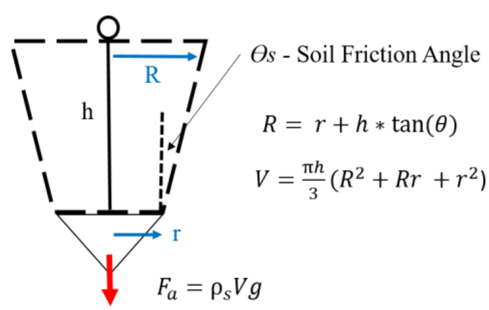

Figure 4. Force related with screw type anchors.

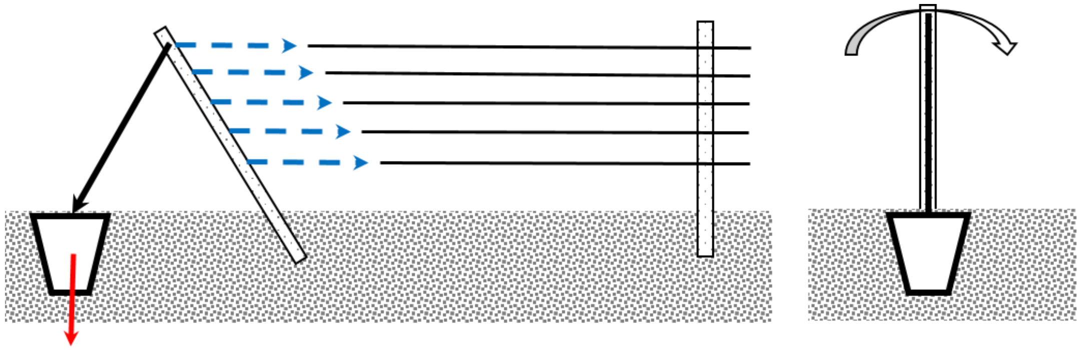

Figure 5. Typical anchor and end post configuration.

Anchors placed in-line with the trellis provide little side-to-side support. Consider alternative anchor setup if side-to-side stability is needed. Figure 6 shows an aerial view of a failed trellis that did not cause the end posts to fail. The end posts in figure 6 where similar style to figure 5.

Figure 6. Ariel view of failed trellis (right) with end posts still standing.

An anchor and wire connected to an end post can reduce the internal shear and moment of a member depending on the location of the wire. In general, a wire will cause a point load. Design for member shear less than allowable shear. Point loads can crush wood members and cause local failures.

Other anchor considerations are concrete ecology blocks (~145 lb ft^{-3}). The ecology blocks will provide 3900 and 7800 lbf (F_a) for a half block (3x3x3 ft) and full block (3x3x6 ft) respectively.

3.4 Beam Theory

Beam theory is used to analyze a member that is loaded axially or laterally and distinct equations exist for each situation. In a formally trained system, buckling will occur if the wire loads all acting on the member exceed Euler's formula for critical buckling load (figure 7(b)). A high slenderness ratio (for long thin posts) will buckle easier than a post with a low slenderness ratio. When superstructure is present, dead loads such as ice, hail, rain, and snow, will add loads and buckling and foundation design need consideration.

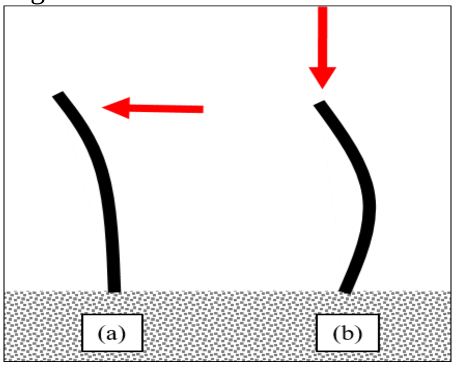

Figure 7. Bending (a) and buckling (b) of a "fixed-end free-end" trellis members.

Beam theory assumes perfect bending with no torsion component and such is the case with wood posts and closed section metal posts of 'moderate length'. For non-symmetrical open section metal shapes such as hat channel, torsion and subsequent buckling need to be addressed. Design should be taken to limit the torsion in a system using open section shapes. Significant reduction in material strength will occur when a member is twisted beyond its ultimate yield.

3.5 Wire and Wire Sag

High tensile wire is typically used to support horticulture and in some cases fabric. For a 12.5ga wire tensioned to 250lb, an additional load of 1200 lbs is permitted [5]. There is no apparent situation when wire becomes the limiting factor of strength for securing horticulture and fruit loads in between trellis members. **If trellis members are not fixed and allowed to pivot (lean), the load on the wire becomes cumulative to adjacent members and can potentially cause overloading.**

Consider this: a 12.5ga wire is not sufficient to 'lift up' a half ecology block or a 6" dia screw anchor, 5 ft deep in 105 lb ft^{-3} soil. Therefore, adequately size anchor-to-end-post wire(s) based on resolved forces in the row, trellis member, and anchor weight (force). A six-wire system tensioned at 250lbs each, will pre-stress a member by 1500 lbs.

Wire will sag according to a catenary curve. The equation used to describe wire sag is:

$$\Delta = (W * S^2) / 8T$$

Where: Δ = Wire sag (ft), W = weight of distributed load (lb ft^{-1}), S = wire span (ft), T = Tension (lb). Wire tensioned at 250lbs with a 100ft and 500ft span will sag approximately 1.6in and 3.3ft, respectively. A short wire span can provide additional support for trellis members if designed to do so.

3.6 Fruit Load

Fruit loading is not a significant factor for vertical wood posts (3-4-5") with a 'normal' span using 12.5ga wire. A normal wire span has enough capacity for heavy fruit loads between trellis members. Branches will also support some fruit load even in formally trained systems.

Fruit loads should be included for angled canopies or when a vertical system starts to lean (see section 3.1). Two common trellis structures for angled canopies are shown in figure 9. Fruit loads on an intra-row brace (a) system will be transferred to each member and their respective soil structure. **It is not correct to assume an intra-row brace will provide additional support in-lieu of embedment depth. Leaning angled posts are an indication of improper embedment.**

A similar concept that was used to predict wind loading can be applied to predict fruit loads on angled members. Fruit can either be broken down into formally trained loads (fruit per linear foot) or informal loads (density based).

Consider this: a 12 ft tall angled trellis (figure 8a) with 14 ft spacing, growing 125 (900lb) bins/ac will add 1044lbs to a trellis member at a 30ft span. This load would be equivalent to 15% of an ultimate yield stress for a wood post. The same trellis growing 85 (900lb) bin/ac would add an equivalent load equal to 10% of the ultimate yield stress. Decrease span accordingly.

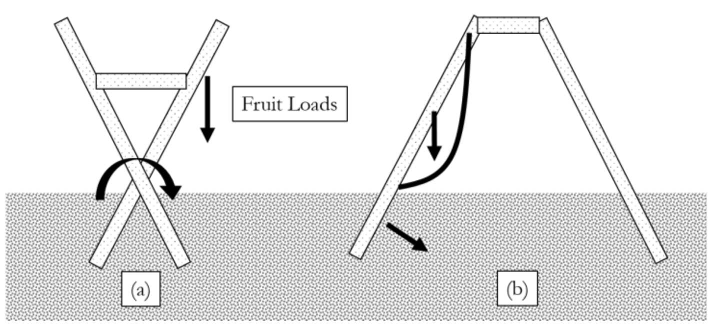

Figure 8. Two common angled canopy configurations: (a) intra-row bracing and (b) inter-row bracing.

Angled trellises are statically indeterminate and need proper design considerations for shear, moment, and deflection in the member. Connection members such as bolts, nails, and wires should be sized correctly. Likewise, welding steel members requires a professional skilled in the art. In general, braces will reduce the shear and moment within a member. For “fixed-end free-end” members, the maximum shear and moment are at ground level.

Two members placed (almost) in plane with each other, as in figure 8(a), will have less lateral soil pressure available if one member begins to disrupt the foundation. Disturbing the soil effectively decreases the lateral pressure capacity of the remaining soil. **Increasing embedment depth will reduce the risk of the aforementioned.** Angled trellis members should not be considered isolated posts with respect to lateral soil pressure (section 3.1).

4.0 Trellis Engineering Model (TEM)

The trellis engineering model was developed using the critera from sections 3.1-3.3 described above. The purpose of the TEM is to provide a simple baseline for planning or evaluating a trellis system. The TEM is conservative from an engineering analysis point of view. TEM output(s) are shown in Figure 10 depicting span versus wood post diameter for a given height, wind speed, and post member design value.

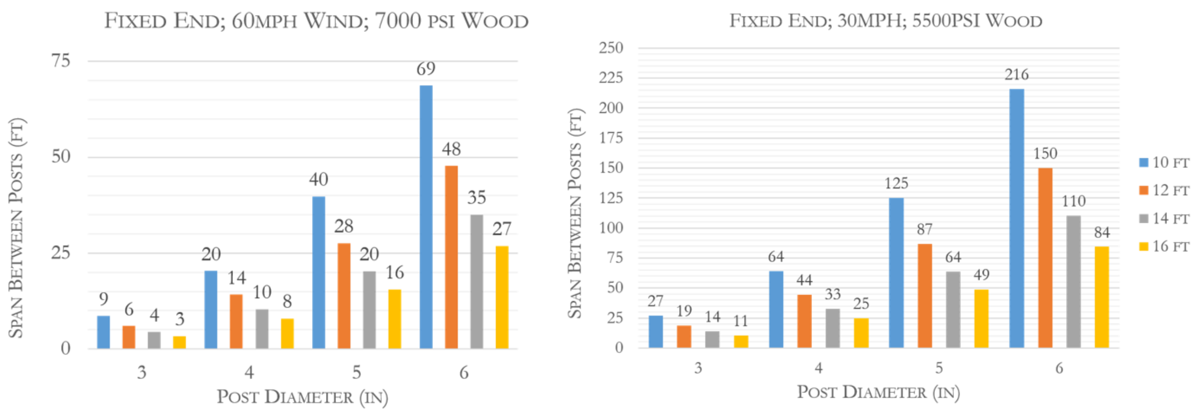

Figure 9. Trellis Engineering Model used to predict trellis member span versus diameter for 4 trellis heights.

The TEM is interactive which allows users to change input variables. Figure 9 shows a TEM output with different input variables.

5.0 Testing

Tests were performed on 30 treated posts bought from local suppliers in central WA. It was not the scope of this project to evaluate suppliers’ material quality. Consider material quality when predicting the trellis span using the TEM. ***Wood is a biological material and strength decreases for knots, splits, young wood, and high moisture content. A higher factor of safety will reduce the risk of this variance.**

For example: the Timber Pile Design and Construction Manual from the Timber Piling Counsel of the American Wood Preserves Institute uses an allowable bending stress for treated round southern pine piles as 2400 psi [6] but reduces by 10% for a > 10yr application. Extreme outdoor conditions will also decrease the allowable stress value of wood members.

In theory, a treated pine wood member will fail around 7000psi. The actual value used in practice is equated to application use, i.e. a shelter for people uses a lower design value than a pump-house. Risk and cost can be adjusted in these values but sound judgement should be used by someone skilled in the art of mechanics and materials.

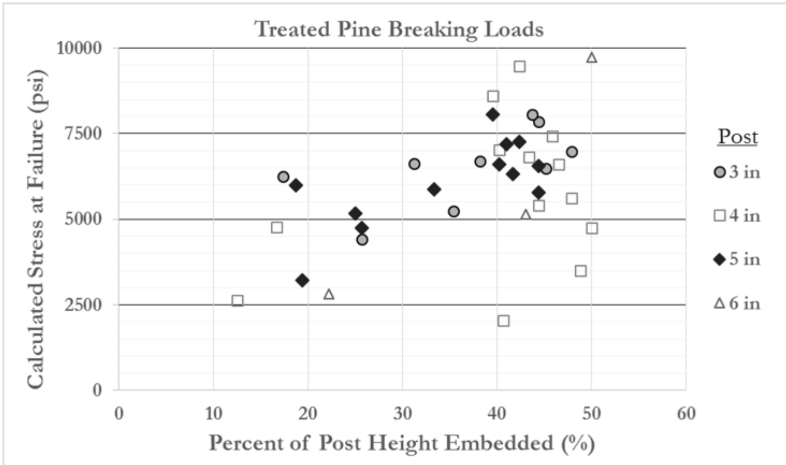

Figure 10. Results for pulling tests on 30 treated pine posts in Quincy type soil.

6.0 Superstructures

The TEM model can be used to determine wind loads for a solid wall, resembling a fabric installed vertically on an outside row. Other considerations when fabric is used to enclose an orchard are dead loads including snow, rain, and hail. Refer to ASCE 7 section 7 for snow loads and section 8 for values of rain loads. A permanent superstructure should be considered a building and designed accordingly. Additional loads will increase the required axial strength of each superstructure member. It is more probable that the fabric will be the limiting factor, depending on installation style, and fail before a wire or trellis member. This is largely dependent upon the setup of the wires in relationship to trellis members and spacing.

The pressure coefficient associated with a seasonal superstructure can be assumed as an ‘agricultural building’. Pressure coefficients given in figure 101-8 [1] should be used to estimate uplift force. Pressure coefficients of 0.2 for windward side and 0.7 for leeward side roofs seem reasonable for an enclosed superstructure. In general, a trellis system is not likely to lift from the soil by means of uplift force on the fabric. However, good judgement is needed when considering the connection between the fabric and posts and additional foundational collars or anchors will help secure trellises that are not connected to individual trees. Trees themselves can act as anchors in a formally trained system.

Disclaimers and General Assumptions

This information is intended to be used to provide fundamental (preliminary) understanding of principle variables acting on a trellis system. For the design of an actual trellis, a competent professional should be consulted.

Wood post refers generally to treated pin post typically found at an orchard supply company in Eastern Washington. Trees do not contribute to resistance loading. Thermal changes were neglected. Trellis heights are less than 15ft for wind calculations. A prerequisite understanding of listed reference material.

References

[1] Midwest Plan Service- Structures and Environment Handbook. 1983. Iowa State University, Ames, IA 50011.

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[3] American Society of Agricultural and Biological Engineers. Shallow Post and Pier Foundation. ANSI/ASABE EP486.2. 2012.

[4] International Code Council. International Building Code, Soils and Foundation (Chp 18). 2009.

[6] Collin, J.G. Timber Pile Design and Construction Manual. Timber Piling Council, American Wood Preservers Institute. 2002.

[7] Government of Saskatchewan. 2017. Using mobile windbreak fences for winter feeding on pastures and cropland. Retrieved from: https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/livestock/cattle-poultry-and-other-livestock/cattle/portable-windbreak-fences

[8] Knapp, John W. 1982. How to Build Orchard and Vineyard Trellises with USS Max-Ten 200 High-Tensile Fence Wire. USS Catalog No. T-111578, U.S.A.

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[9] Van Dalfsen, K. Bert. 1989. Support Systems for High-Density Orchards. “First presented at the British Columbia Horticultural Forum, November 5, 1986. Providence of British Columbia, Ministry of Agriculture and Fisheries, Victoria B.C., Canada. ISBN-0-7726-1009-6.

[10] Mollah, M. R. 1989. Review of Trellis Structures for Horticultural Crops. Department of Agriculture and Rural Affairs. Mildura, Victoria. ISBN 0-7306-0546-9.

4. Executive Summary

Trellis system are a collection of individual components that must collectively work together to resist external loading. The weakest link often gets exploited and creates a potential for costly capital failure. A model to predict loads on trellises was developed as a tool to aid in the analysis and planning of current and future trellis systems.

The trellis equation is a product of multiple variables, for which numerous solutions exist. However, each component must be sized according to the collective system for proper trellis design. The most important factors are: trellis style, soil structure, canopy wind loading, and span between members.

The trellis engineering model can be used to determine canopy wind loading, embedment depth for a give soil type and span between posts. Wind loads can be sized according to canopy style where denser canopies will 'catch' more wind. Trellis members require an embedment depth that results in a proper fixed base; deeper for weaker soils. After wind, soil, and some other variables are quantified, the span between members gives the orchardist the plan to implement a proper trellis for their crop.

Each trellis is a unique system when all variables are assembled together. It is important to understand each trellis system's structural integrity and the potential areas of weakness in that (style) system.

The following are good practices and considerations for trellis design and planning:

- Design the trellis to protect capital investment
- Design the trellis to a horticulture preference
- Use the TrellX model to estimate wind loads
- Conduct soil tests at locations in orchard where soil depth may vary: hills and valleys
- Use restraints in shallow soils
- Increase embedment depth for angled trellis with intra-row braces
- Fruit loads are additive on angled canopies
- Minimize twisting (torsion) when using non-symmetric metal shapes
- Use the TrellX model to estimate trellis span between posts
- Consider unexpected loads and use a factor of safety to reduce risk of failure
- Size secondary trellises properly when 'adding on' to existing trellis
- Limit pre-stressing members caused from overtightening wires and cables
- Consult an expert