BIOCLIMATIC KIT HOUSE IN MOOREA, FRENCH POLYNESIA

A STRUCTURAL ASSESSMENT

CATHERINE MILLER

MAY 13, 2009

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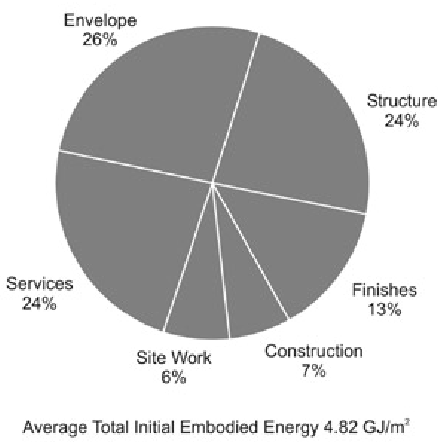
ABSTRACT

In order to achieve the goals of improving the environmental and economic sustainability of the Bioclimatic Kit Houses in Moorea while simultaneously encouraging growth of the local timber industry, I analyzed the structural design of the homes with the intent of decreasing material input through a more efficient framing scheme and replacing imported Douglas Fir with locally grown Caribbean Pine. After calculating the anticipated dead, live, and wind loads according to the National Design Specifications for Wood Construction, it was ascertained that Southern Pine (an approximate estimate for the mechanical properties of Caribbean Pine) would be an appropriate substitute for Douglas Fir, and the total volume of structural timber in the outer walls and roof could be reduced by forty-three percent.

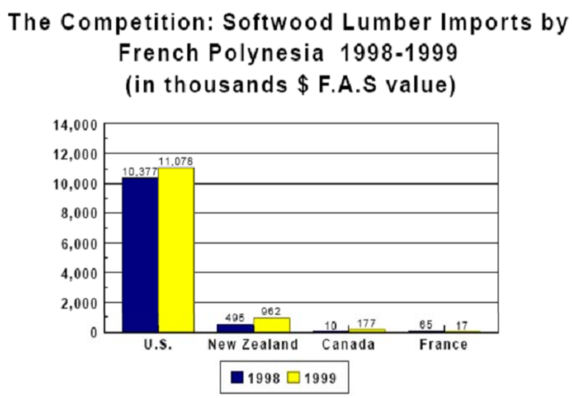
BACKGROUND

The Bioclimatic Kit Houses in Moorea, French Polynesia are currently designed as one-story, single-family residences using Douglas-Fir timber imported from the United States. Due to the significant energy impacts attributed to the structure of a building (as shown below) and the high economic and environmental costs of importing lumber from the United States, it is imperative that, in order to decrease the detrimental environmental affects of the Kit House Project, structural solutions are implemented.

Portions of Embodied Energy in a Building



Lumber Imports to French Polynesia



PROJECT GOALS

In order to improve the overall environmental sustainability of the timber-framed houses, I will analyze the viability of two solutions

- Efficient Framing
- Local Material Selection

The current design standard is to place joists and studs at either 12" or 16" on center in order to limit the deflection of the gypsum particleboard. The gypsum board is a flexible material that is prone to deforming between the points at which it is attached to stiffer structural elements. This deformation results in a wall that appears to sway from joist to joist like a wave. Although it has been practice to limit spacing of joists and studs in order to accommodate for the flexibility of the particleboard, industry now accepts a spacing of 24" on center in order to decrease material inputs while maintaining an adequate appearance for the walls. Therefore, I will carry out structural calculations ascertaining the behavior of the building under this increased spacing, taking into account dead, live, and wind loads particular to residential housing in French Polynesia. Also, in order to decrease the entire volume of the timber needed, I will attempt to reduce member size from 4x4s or 3x4s to 2x4s where possible.

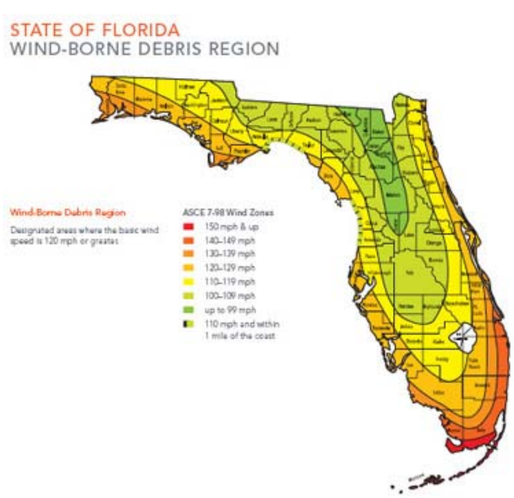
In addition to attempting to decrease the volume of material needed in the houses, it is also my goal to replace the Douglas Fir with locally grown Caribbean Pine. Although, until recently, the timber industry on the island has been limited, it is currently experiencing growth in capabilities and capacity. I hope that by finding replacement of Douglas Fir with Caribbean Pine feasible, I will assist in the development of this local industry while simultaneously decreasing the environmental and economic burden of shipping timber from the United States.

APPROACH

In calculating the expected load demands on the houses in Moorea, I used United States Building Codes and the National Design Specifications for Wood Construction. Although specific French Polynesian codes do exist, they are in French, making translation and understanding difficult, and I have no familiarity in using them. These challenges decreased my confidence in the ability to attain precise results, leading me to assume that US Building Codes would be both sufficient and more accurate for our design. Another challenge I faced, however, was the lack of knowledge about the weights of various materials in the current design. To determine dead loads, therefore, I used approximate values supplied by the Wood Frame Construction Manual for One to Two Story Dwellings. Additionally, I was not supplied extensive roof framing plans or details of internal walls, so I concentrated my structural calculations on the vertical elements in the roof truss and the external walls.

To calculate the wind load, I used a Basic Wind Speed of 150mph, which corresponds to the largest Basic Wind Speed in the United States. It occurs off the coast of Florida, and represents a Wind-Borne Debris Region (as seen in the following map of Basic Wind Speeds).

Basic Wind Speeds for the Coast of Florida, ASCE 7.98



After determining the Basic Wind Speed, I applied an Importance Factor of 1 (residential dwelling), a topographical factor of 1, and an Exposure Class C (flat, open country in hurricane-prone regions). With this information, I was able to determine the expected pressures, or loads, on the different regions (roof, wall, overhang, etc.) of the house. In assigning load pressures to given areas, I included the overhang along the top ridge of the house as an eave. This is significant as the expected loads are dramatically larger for overhangs / eaves than for either walls or portions of the roof attached to the roof truss.

In order to achieve the goal of using Caribbean Pine rather than Dougals Fir, I calculated load capacities for both Douglas Fir (to determine that, at a minimum, the amount of Douglas-Fir can be reduced) as well as Southern Pine. Although I intended to use precise material properties of the Caribbean Pine available on Moorea, our local mentors and advisors on the island could not determine this quantitative data from the lumber mills. Additionally, there are no values supplied for Caribbean Pine in the US Building Codes. Therefore, in order to estimate the capacity of Caribbean Pine I used Southern Pine data. To accommodate further research, however, my structural calculations are designed so that if the capacity of Caribbean Pine in bending, tension, and compression were known, it could be easily and quickly verified that this capacity either is or is not sufficient for load demands.

RESULTS / DISCUSSION

To determine the maximum loading scenario, I checked wind loads in both the transverse and horizontal directions. Due to the severe winds expected, as well as the minimal dead and live loads attributed to single-story timber framed homes, the axial loading of the roof trusses and external wall members is primarily in tension. Concurrently, due to the wind loads, the elements are subjected to significant bending forces.

Despite these force demands, the roof truss is able to withstand both the tensile and bending forces, independently of one another, with just three 4x4 members (in both Douglas-Fir and Southern Pine) rather than the current design of twenty-six members (mixed 2x4s, 3x4s, and 4x4s). However, when applying both bending and tension simultaneously to the roof truss, the Southern Pine will behave adequately, but the demand for the Douglas-Fir is slightly above capacity. In using three 4x4 members the spacing requirement of a maximum distance of 24" is also not satisfied. In adding members (2x4s) to meet the spacing requirement, the bending and tension loads will be decreased from the design of only three 4x4 members. Hence, behavior is expected to be well within capacity for the roof truss.

For the design of external walls, spacing was placed at 24" on center. Also, in keeping with attempts at decreasing the total volume of the wood used, I used only four 4x4s and twelve 2x4s on the short side of the building and five 4x4s and 14 2x4s on the long side of the building. This is a significant savings on the original design using 28 and 32 members (short side and long side, respectively) of mixed 2x4s, 3x4s, and 4x4s. The external walls behave well under tension, bending, and combined tension and bending for both Douglas Fir and Southern Pine under this adjusted framing scheme.

Through structural redesign of the Bioclimatic Kit houses, I was able to decrease the volume of our roof truss material by 42%, our vertical roof elements along the peak of the roof by 39%, and our external walls by 45%. The total volumetric reduction in timber material is 43%. Also, I verified that Southern Pine is a viable replacement for Douglas Fir. In conclusion, through a more efficient structural design and replacement of imported building materials with locally grown and milled wood, the economic and environmental sustainability of the Moorea Housing Project has been improved.

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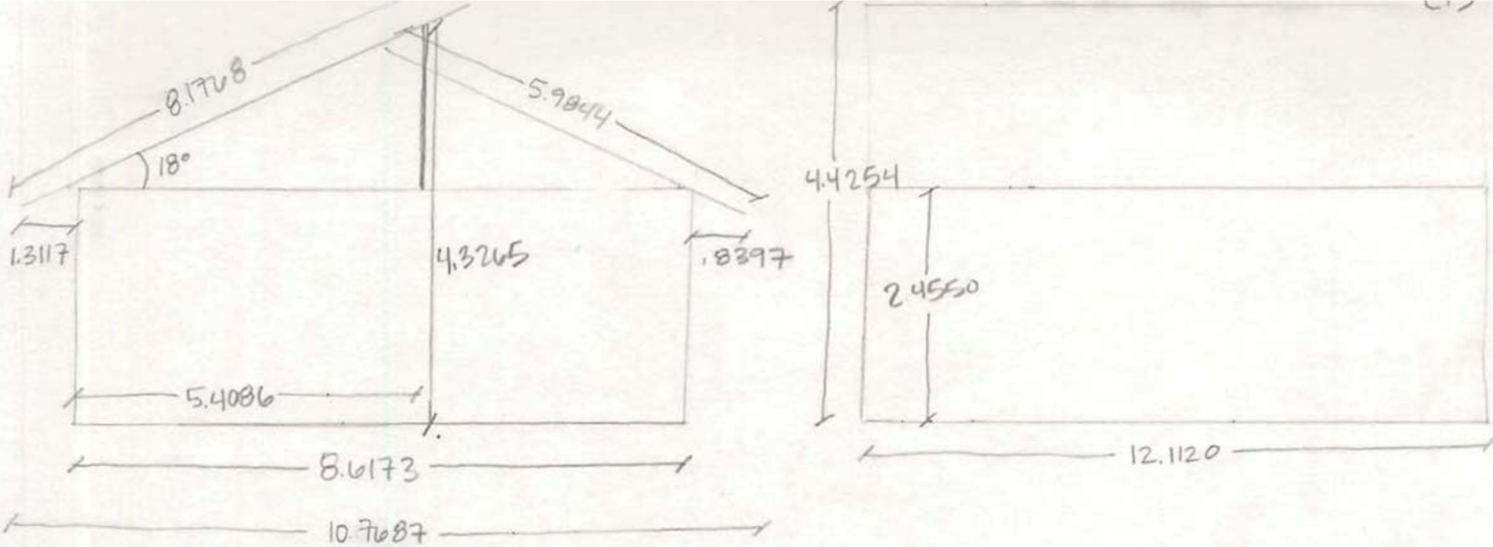


LOADS

DEAD: (based on 2000 IBC)

ROOF	10 psf
CEILING	5 psf
FLOOR	10 psf
WALLS	11 psf

LIVE:

ROOF	20 psf
FLOOR	40 psf

WIND

- Basic wind speed = 150 mph (approximate, based on design loads for the Florida coast)
- Importance Factor = 1.0 (residential dwelling)
- Kzt (topographical effect factor) = 1.0
- Enclosed Building
- Exposure C: flat open country in hurricane-prone regions
  - $\lambda = 1.21$
- mean roof height - $2.4550 + \frac{1.9704}{2} = 3.44m = 11.35 ft$
- a-dimension for end zone
  - lesser of
    - (1) 10% (8.6173) = .862 m
    - (2) .4 × 3.44m = 1.376m
  - Not less than
    - (1) .04 (8.6173)
    - (2) 3 ft ← governs (.909m) $2a = 1.82m$

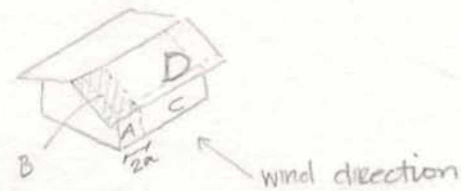
TRANSVERSE WIND LOAD

$p_s = \lambda K_{zt} I p_{s30} = 1.21 p_{s30}$

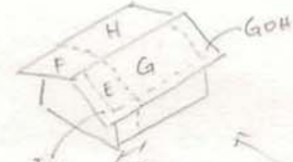
($\theta = 18°$, linearly interpolated between p_{s30} for 15° and 20°)

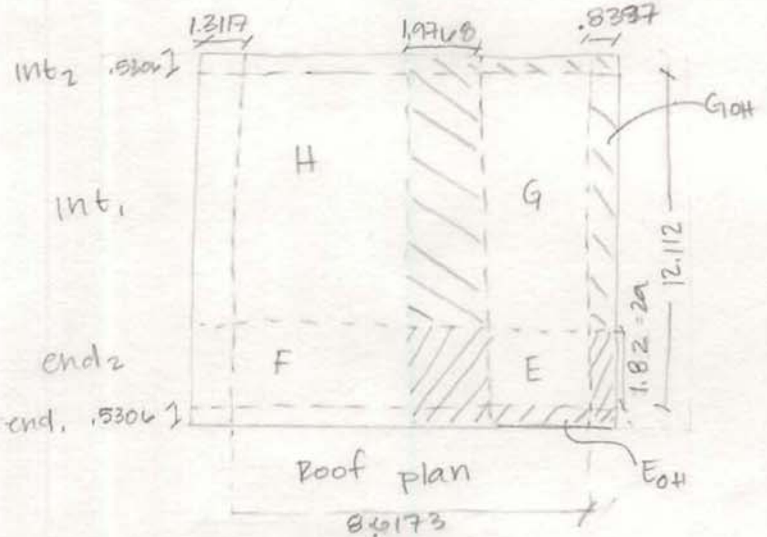
Zone	p_{s30}	p_s (psf)
A	47.4	57.354
B	-13.76	-16.6496
C	31.66	38.3086
D	-9.02	-10.9142
E	-42.9	-51.909
F	-27.12	-32.8152
G	-29.8	-36.058
H	-20.88	-25.2648
E_{OH}	-60	-72.6
G_{OH}	-47	-56.87

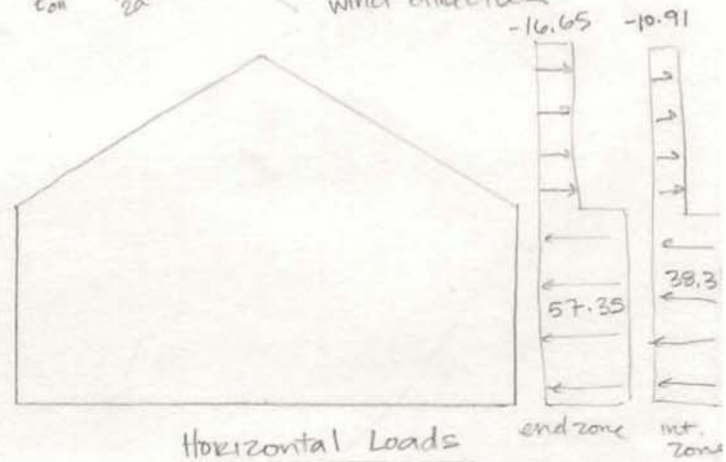
Horizontal load zones:



Vertical load zones:







Vertical Loads

$W_{end_1} = -32.82(4.3357 \times 3.3) - 72.6(4.3357 \times 3.3)$

$= -1508$ plf

$W_{end_2} = -32.82(4.3357 \cdot 3.3) - 72.6(1.9768 \times 3.3)$
$- 51.9(1.2698 \times 3.3) - 72.6(.8397 \times 3.3)$

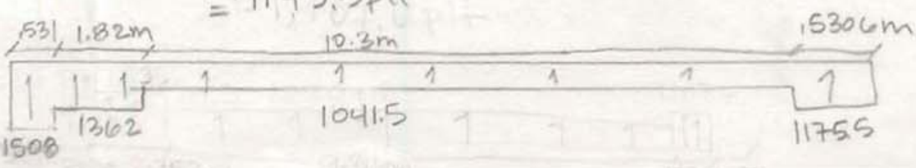
$= -1361.8$ plf

$W_{int_1} = [-25.26(4.3357) - 56.9(1.9768) - 36.1(1.2698)$
$- 56.9(.8397)] \times 3.3$

$= -1041.53$

$W_{int_2} = [-25.26(4.3357) - 56.9(4.3357)] \times 3.3$

$= -1175.5$ plf



Horizontal Loads

$W_{end} = 57.35\left(\frac{2.455 \times 3.3}{2}\right) - 16.65(1.9704 \times 3.3)$

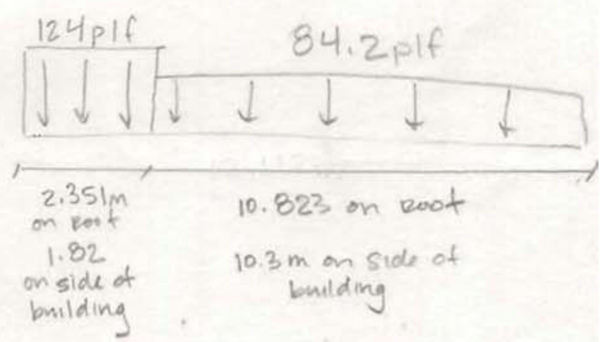
$= 232.31 - 108.26$

$= 124.05$ plf

$W_{int} = 38.31\left(\frac{2.455 \times 3.3}{2}\right) - 10.91(1.9704 \times$

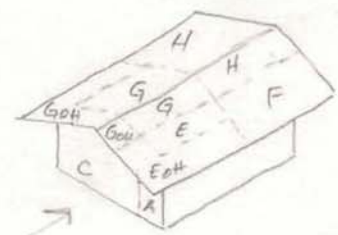
$= 155.1842 - 70.94$

$= 84.244$ plf



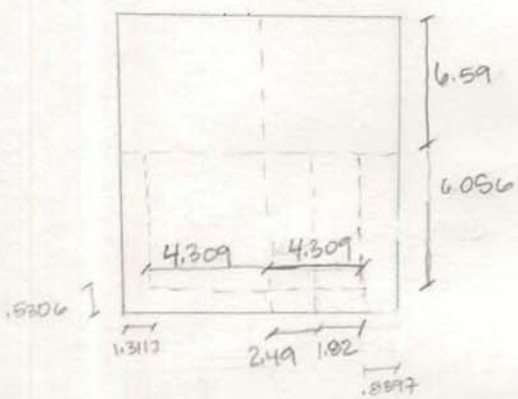
ZONE	P_{S30}	$P_S = 1.21 \times P_{S30}$
A	35.7	43.197
B	-18.5	-22.385
C	23.7	28.677
D	-11.0	-13.31
E	-42.9	-51.91
F	-24.4	-29.524
G	-29.8	-36.06
H	-18.9	-22.87
E_{OH}	-60	-72.6
G_{OH}	-47	-56.87

Horizontal + Vertical Load zones



wind direction

Vertical Loads



$-56.87(6.587 \times 3.3) - 22.87(6.587 \times 3.3) = -1733.3\,plf$

$-56.87(.531 \times 3.3) - 36.06(6.056 \times 3.3) - 22.9(6.59 \times 3.3)$

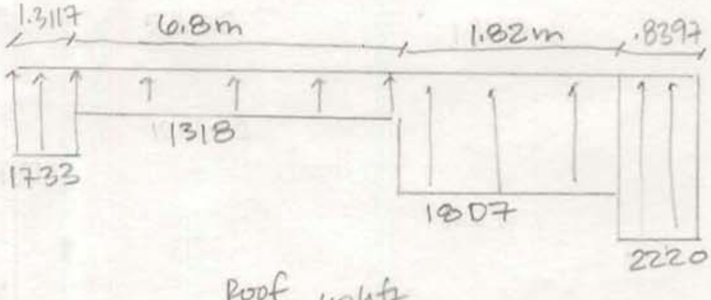
$= -1318.3\,plf$

$-72.6(.531 \times 3.3) - 51.91(6.056 \times 3.3) - 29.524 \times (6.59 \times 3.3)$

$= -1806.7\,plf$

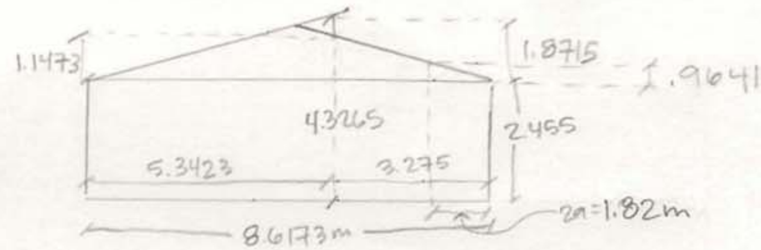
$-72.6(6.587 \times 3.3) - 29.524(6.587 \times 3.3)$

$= -2219.88\,plf$



Roof uplift

Horizontal Loads



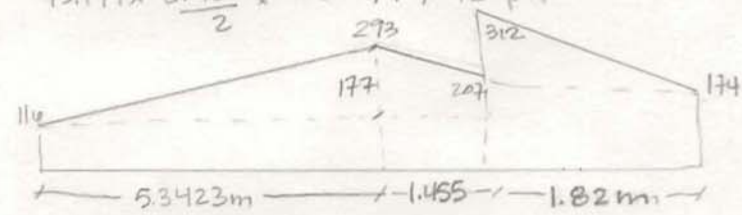
$28.677 \times \frac{2.455}{2} \times 3.3 = 116.16\,plf$

$28.677 \times \left(\frac{2.455}{2} + 1.8715\right) \times 3.3 = 293.27\,plf$

$28.677 \times \left(\frac{2.455}{2} + .9641\right) \times 3.3 = 207.4\,plf$

$43.197 \times \left(\frac{2.455}{2} + .9641\right) \times 3.3 = 312.41\,plf$

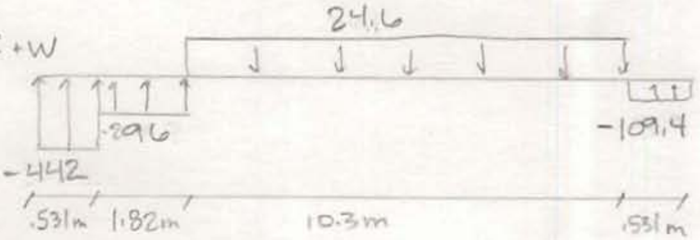
$43.197 \times \frac{2.455}{2} \times 3.3 = 174.98\,plf$



LOAD COMBINATIONS

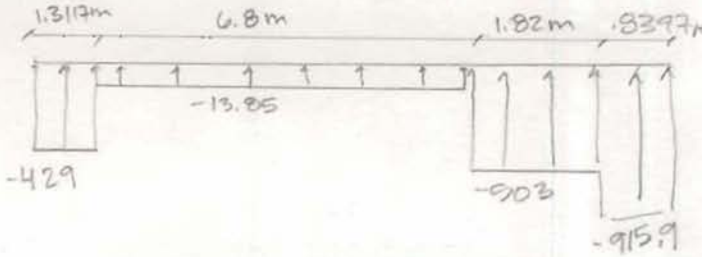
ROOF: $D + L_R + W$ (axial loading)

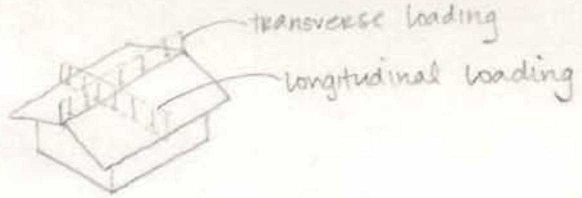
transverse: $(10+20\text{ psf})(10.7687\text{ m} \times \frac{3.3\text{ ft}}{\text{m}}) + W = 1066.1\text{ plf} + W$



longitudinal: $(10+20\text{ psf})(12.112 + .5306 \times 2) \times 3.3 + W$

$= 1304.15 + W$





ROOF: (bending): W

end zone governs: 16.65 psf (transverse)

43.197 psf (longitudinal)

DESIGN FOR TENSION & COMPRESSION

compression: 46.1 plf

tension: -916 plf

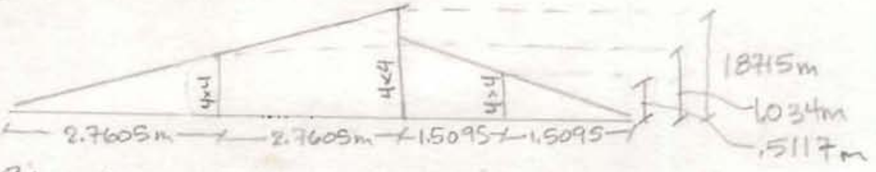
S (4×4 member size) = 7.146 in^3 $A = 12.25\text{ in}^2$

S (2×4 member size) = 3.063 in^3 $A = 5.25\text{ in}^2$

Roof system: 5 triangular systems, one system along length

Assume: 3 4×4 every 2.993m along transverse direction

Roof truss:



tension: $\frac{-916\text{ plf}}{13.173\text{ m}}\left(\frac{\text{m}}{3.3\text{ ft}}\right) = 21.07\text{ psf}$

$21.07\text{ psf}\left(2.993\text{ m} \times 3.3\frac{\text{ft}}{\text{m}}\right)\left(2.7605\text{ m} \cdot 3.3\frac{\text{ft}}{\text{m}}\right) = 1895.9\text{ lb}$

$f_t = \frac{1895.9\text{ lb}}{12.25\text{ in}^2} = 154.76\text{ psi}$

compression: $\frac{24.6\text{ lb/ft}}{10.7687\text{ m}}\left(\frac{\text{m}}{3.3\text{ ft}}\right) = .692\text{ psf}$

$f_c = .692\frac{\text{lb}}{\text{ft}^2}\left(2.993\text{ m} \times \frac{3.3\text{ ft}}{\text{m}}\right)\left(2.7605\text{ m} \times \frac{3.3\text{ ft}}{\text{m}}\right) = \frac{62.3\text{ lb}}{A} = 5.08\text{ psi}$

Douglas Fir-Larch (Standard 2-4" thick + 2-4" wide)

$F_t = 375\text{ psi}$

$F_c = 1400\text{ psi}$

Adjustment Factors:

C_M: assume moisture content < 19% = 1.0

C_{fu}: flat use factor = 1.0

C_F : size factor = 1.0 for F_t + F_c

C_D : Load duration factor = 1.6 for wind loads

C_t = 1.0 (temperature factor)

C_i = 1.0 (incising factor)

C_P = 1.0 (column stability factor)

$F_t' = F_t \times C_D \times C_M \times C_t \times C_F \times C_i$ = 600 psi

$F_c' = F_c \times C_D \times C_M \times C_t \times C_F \times C_i \times C_P$ = 2240 psi

600 psi > 155 psi ✓

2240 psi > 5 psi ✓

∴ ok in pure tension + compression for reduced members to 3 4×4s.

Standard Southern Pine (2-4" thick + 4" wide)

F_t = 350 psi

F_c = 1500 psi

F_t' = 1.6 (350) = 560 psi

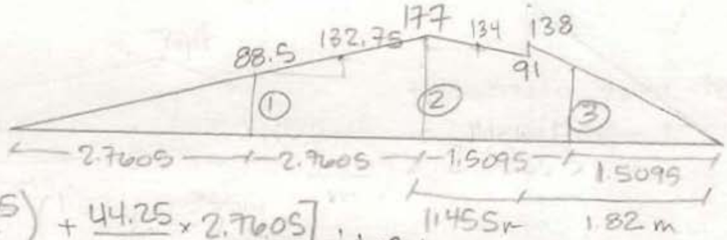
F_c' = 1.6 (1500 psi) = 2400 psi

560 > 155 psi ✓

2400 > 5 psi ✓

∴ ok in pure tension + compression for 3 4×4 Southern pine

BENDING



① $\left[\frac{88.5\text{plf}}{2} \times 2.7605 + 88.5\left(\frac{2.7605}{2}\right) + \frac{44.25}{2} \times \frac{2.7605}{2}\right] \div 1.034 = \omega_1 = 265.8$ plf

$M_1 = \frac{\omega_1 L_1^2}{8} = \frac{266 \times (1.034 \times 3.3)^2}{8} = 386.8$ lb-ft

② $\left[132.75 \times \frac{2.7605}{2} + \frac{44.25}{2} \times \frac{2.7605}{2} + \frac{134}{2} \times 1.5095 + \frac{43}{2} \times \frac{1.5095}{2}\right] \div 1.8715 = 177$ plf

$M_2 = \frac{\omega_2 L_2^2}{8} = \frac{177(1.8715 \times 3.3)^2}{8} = 843.6$ lb-ft

③ $\left[138 \times \frac{1.82}{2} + 91 \times \frac{1.455}{2} + \frac{43}{2} \times \frac{1.455}{2}\right] \div .5117 = 405.36$ lb/ft

$$M_3 = \frac{W_3 L_3^2}{8} = \frac{405\,(.5117 \times 3.3)^2}{8} = 144.5 \text{ lb-ft}$$

① From opposite side:

$$\tfrac{1}{2}(138)(1.82) + 58\left(\frac{2.7605}{2} + 2.7605 - 1.82\right) + \frac{(132.75 - 58)}{2}\left(\frac{2.7605}{2} + \frac{2.7605 -}{1.82}\right)$$

$$= \frac{346.9}{1.034} = 335.5 \ \frac{\text{lb}}{\text{ft}}$$

$$M_1 = \frac{WL^2}{8} = \frac{335 \times (1.034 \times 3.3)^2}{8} = 488 \text{ lb-ft}$$

$$f_{b\,max} = \frac{844}{S} = \frac{844 \text{ lb-ft}}{7.146 \text{ in}^3} \times \frac{12 \text{ in}}{\text{ft}} = 1417.3 \text{ psi}$$

F'_b for Douglas-Fir Larch

Construction: 1.6 × 1000 psi = 1600 psi ✓ok
No 2 : 1.6 × 900 psi = 1440 psi ✓ok

F'_b for Southern Pine

Construction: 1.6 × 1100 = 1760 psi ✓ok
No 2 Non-Dense: 1.6 × 1350 = 2160 psi ✓ok

3 4×4 timber members sufficient for bending loads as long as construction or No 2 timber (at least) is used.

COMBINED TENSION + BENDING FOR ROOF

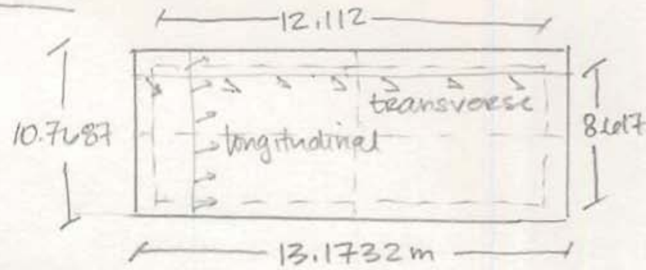
$$\frac{f_t}{F'_t} + \frac{f_b}{F'_b} \leq 1.0$$

$$\frac{154.7}{600} + \frac{1417}{1440} = 1.24 \quad \text{not ok}$$

$$\frac{154.7}{600} + \frac{1417}{2160} = .91 \quad \text{ok}$$

Under combined tension and bending for douglas fir, only 3 4×4 members is inadequate. However, code requires members be placed 24" o.c., so this will decrease both bending and compression loads to a point that should be adequate for combined loading.
Combined bending + tension adequate for Southern Pine.

LOAD COMBINATIONS FOR EXTERIOR WALLS



$D_{Roof} + D_{ceiling} + D_{walls} + L_{Roof} + W$

LOAD CASE 1: TRANSVERSE

$D_{Roof} = 8.1768\,m \times 3.3\,\frac{m}{ft} \times 10\,psf = 270\,plf$

$D_{ceiling} = \frac{8.6173}{2} \times 3.3 \times 5\,psf = 71.\,plf$

$D_{walls} = 2.445 \times 3.3 \times 11\,psf = 89\,plf$

$L_{Roof} = 8.1768 \times 3.3 \times 20 = 540\,plf$

$W_{max} = 124\,plf$ (bending load)

$W_{vertical\ load} = [1508 \times .531 \times 3.3 + 1362 \times 1.82 \times 3.3 + 1041.5 \times 10.3 \times 3.3 + 1175.5 \times .5306 \times 3.3] \div 2 \div \left(\frac{10.7687}{2}\right) = -1358.6\,plf$

total vertical load: $970 - 1359 = -389\,plf$

LOAD CASE 2: LONGITUDINAL

$D_{Roof} = 6.5866 \times 3.3 \times 10\,psf = 217.\,plf$

$D_{ceiling} = 6.056 \times 3.3 \times 5 = 100\,plf$

$D_{walls} = 2.455 \times 3.3 \times 11 = 89\,plf$

$L_{Roof} = 6.5866 \times 3.3 \times 20 = 434.7\,plf$

$W_{bending,max} = 312\,plf$

$W_{vertical} = (1733 \times 1.3117 \times 3.3 + 1318 \times 6.8 \times 3.3 + 1.82 \times 3.3 \times 1807 + .397 \times 3.3 \times 2220) \div 2 \div 6.5866 = -1244\,plf$

total vertical load: $841 - 1244 = -403\,plf$

check to have studs every 24" o.c. : .606m.

$f_{t_1} = \frac{390 \times (0.606\,m \times 3.3\,\frac{ft}{m})}{12.25\,in^2} = 64\,psi$

$f_{t_2} = \frac{403\,(0.606 \times 3.3)}{12.25} = 66\,psi$

$f_{b1} = \frac{124 \times 0.606 \times 3.3}{7.146} \times \frac{2.455\,m}{3.1979} \times \frac{12\,in}{ft} = 308\,psi$

$$f_{b2} = \frac{312 \times 0.606 \times 3.3}{7.146} \times \frac{2.455}{2.1916} \times \frac{12\text{in}}{\text{ft}} = 1131 \text{ psi}$$

For studs, $C_F = 1.1$, $C_D = 1.6$ $\quad F_b' = 1.1 \times 1.6 \times F_b$

$F_t' = 1.1 \times 1.6 \times F_t$

Douglas Fir-Larch: (Stud)

$F_b = 700 \quad F_t = 450$

$F_b' = 1232$ psi > 1131 ✓ok

$F_t' = 792$ psi > 66 ✓ok

Southern Pine (Stud)

$F_b = 850 \quad F_t = 475$

$F_b' = 1.6 \times F_b \quad F_t = 1.6 \times F_t$

$F_b' = 1360 > 1131$ ✓ok

$F_t' = 760 > 66$ ✓ok

COMBINED TENSION + BENDING

Douglas Fir: $\frac{f_b}{F_b'} + \frac{f_t}{F_t'} = 1.00 \leq 1$ ✓ok

Southern Pine: $\frac{f_b}{F_b'} + \frac{f_t}{F_t'} = .92 \leq 1$ ✓ok

Design values are all for 2-4" thick and 2-4" wide, so it would be possible, at the very least, to use only 2×4s spaced every 24" o.c. rather than the current spacing of 16" o.c.

MATERIAL SAVED

CURRENT ROOF TRUSS DESIGN

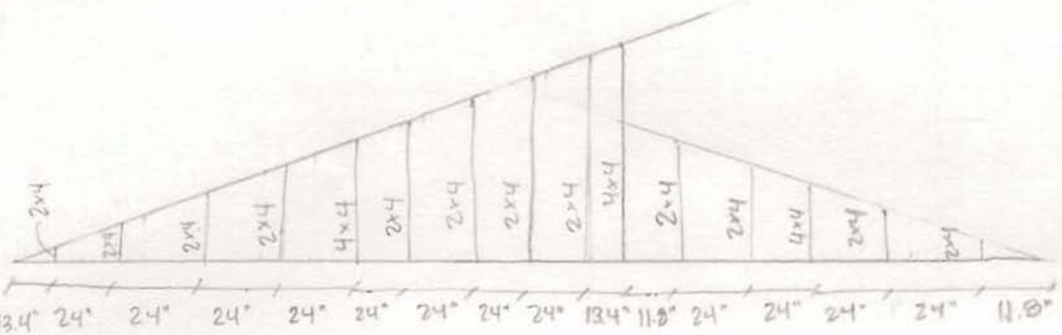
approximately 4 timbers every 1.220m
Average height: 0.93575m
Average size of members: 2.4" × 4" (26 members)

CURRENT ROOF DESIGN ALONG ROOF PEAK

approximately 8 timbers every 2.993m
height = 1.7754m
average size of members: 2.5" × 4" (39 members)

NEW DESIGN RECOMMENDATIONS

TRUSS:



Now, 15 members instead of 26.
Average size: 2.4" × 4"
Average height: 0.93575m

Reduction of material: $\left(2.4\text{in} \times 4\text{in} \times .93575\text{m} \times 3.3\frac{\text{ft}}{\text{m}} \times \frac{12\text{in}}{\text{ft}}\right)(26-15)$

$= 2.26 \text{ ft}^3 \times 5 \text{ trusses} = 11.32 \text{ ft}^3$

$\frac{11.32 \text{ ft}^3}{26.76 \text{ ft}^3} = 42.3\%$ reduction for roof truss

(original volume → 26.76 ft³)

Along roof peak: 4×4s @ 2.9930 O.C., 2×4 @ 23.7" O.C.
total: 5 4×4, 20 2×4 (reduction of 14 members)
average size: 2.4 × 4
height: 1.7754m

Reduction: $\left(\frac{2.5 \times 4 \times 1.7754 \times 3.3}{12 \times 12}\right)(39) - \left(\frac{2.4 \times 4 \times 1.7754 \times 3.3}{12 \times 12}\right)(25)$

$= 6.10 \text{ ft}^3$

$= \frac{6.10}{15.87} = 38.5\%$ reduction

WALLS (EXTERNAL)

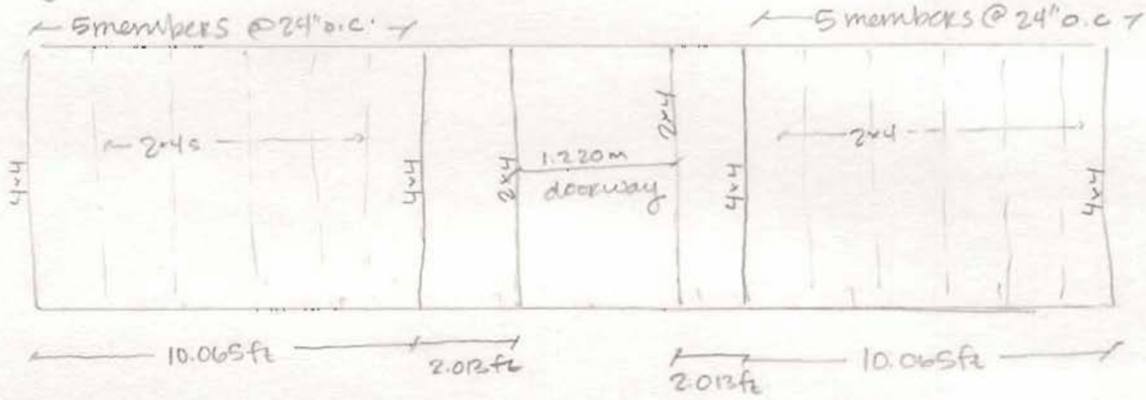
Original design:

approximately 16 2x4s, 7 3x4s, 9 4x4s on long side (32 memb.)
18 2x4s, 6 3x4s, 4 4x4s on short side (28 memb.)

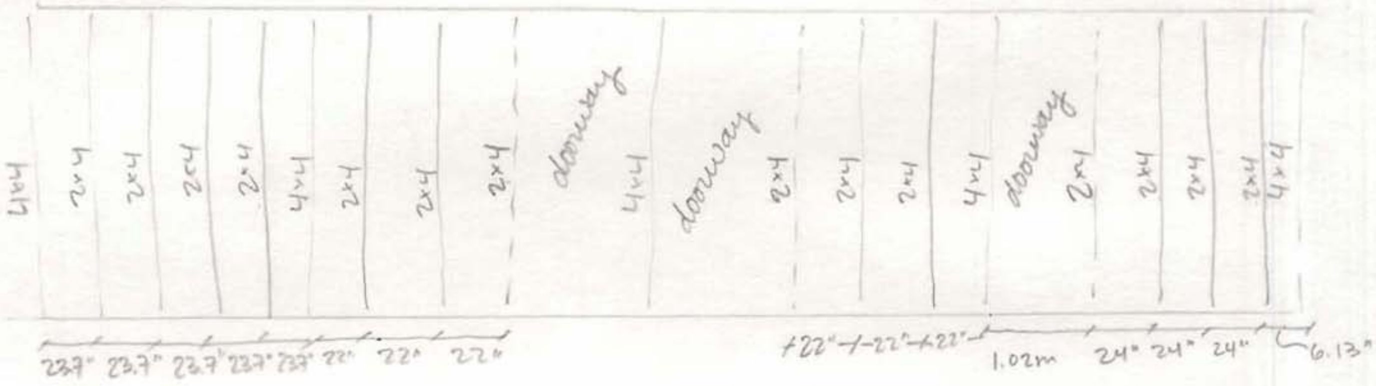
height ≈ 2.26m

avg size on long side: 2.78" x 4"
avg size on short side: 2.5" x 4"

New design: 4 4x4s, 12 2x4s : 16 members (short side)



5 4x4s, 14 2x4s : 19 members long side



Reduction in Material:

$$\left[32\left(\frac{2.78\times4}{12\times12}\times2.26\times3.3\right)+28\left(\frac{2.5\times4}{12\times12}\times2.26\times3.3\right)\right]$$

$$-\left[19\left(\frac{2.53\times4}{12\times12}\times2.26\times3.3\right)+16\left(\frac{2.5\times4}{12\times12}\times2.26\times3.3\right)\right]=32.9\ ft^3-18.2\ ft^3$$

$$\frac{14.68\ ft^3}{32.9\ ft^3}=45\%\text{ reduction}$$

$$\text{Total reduction}=\frac{(11.32+6.1+14.68)}{(26.76+15.87+32.9)}=\underline{\underline{43\%\text{ total reduction}}}$$