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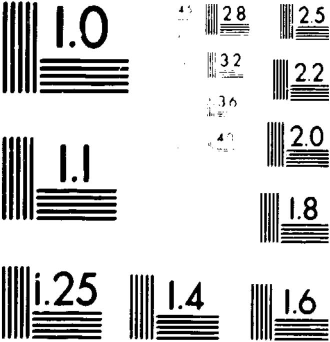

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SRI LANKA

Technical report: Glulam portal frames*

Prepared for the Government of Sri Lanka
by the United Nations Industrial Development Organization,
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Based on the work of C. R. Francis, Timber Engineer

United Nations Industrial Development Organization
Vienna

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1. THE DESIGN OF PORTAL FRAMES

Portal frame structures are widely used for many buildings. Portal frames can be readily made from glulam.

The earliest types of portal frames made in glulam were fabricated from laminates thin enough to be curved around the knee without breaking. Although aesthetically pleasing, these are difficult to make, requiring a jig shaped to the final profile of the frame. If a sharp curve is required, the laminates must be very thin. This wastes a lot of wood in planing, and consumes a large volume of glue in the numerous glue lines.

Considerable effort has gone into the design of portal frames made from straight or tapered members. Straight members are fabricated directly on a beam jig, and two identical tapered members can be sawn from one straight piece of glulam.

The problem which arises with portal frames made from straight members is the fabrication of a rigid moment-resisting joint at the knee. Glulam portal frames are generally made three-hinged, so the joint at the apex need not resist bending moment.

Various solutions have been found to the problem of the knee joint. In Europe, a very large fingerjointer has been made which cuts mating fingers into the leg and the rafter. These are then glued together. Other mechanical joints have been used which include nailed or toothed plates covering the joint and transferring the moment. Steel straps fixed with coach screws into the inside and outside faces have also been used.

An alternative to the uni-planar form of construction is to use a double leg and a single rafter, with a glued joint where the members cross. In larger forms a triple leg and double rafter may be used.

This construction relies entirely on the glue to carry the stress. Consequently factory quality glueing in controlled conditions is essential.

Fig. 1 shows a small building being erected using this type of portal frame.

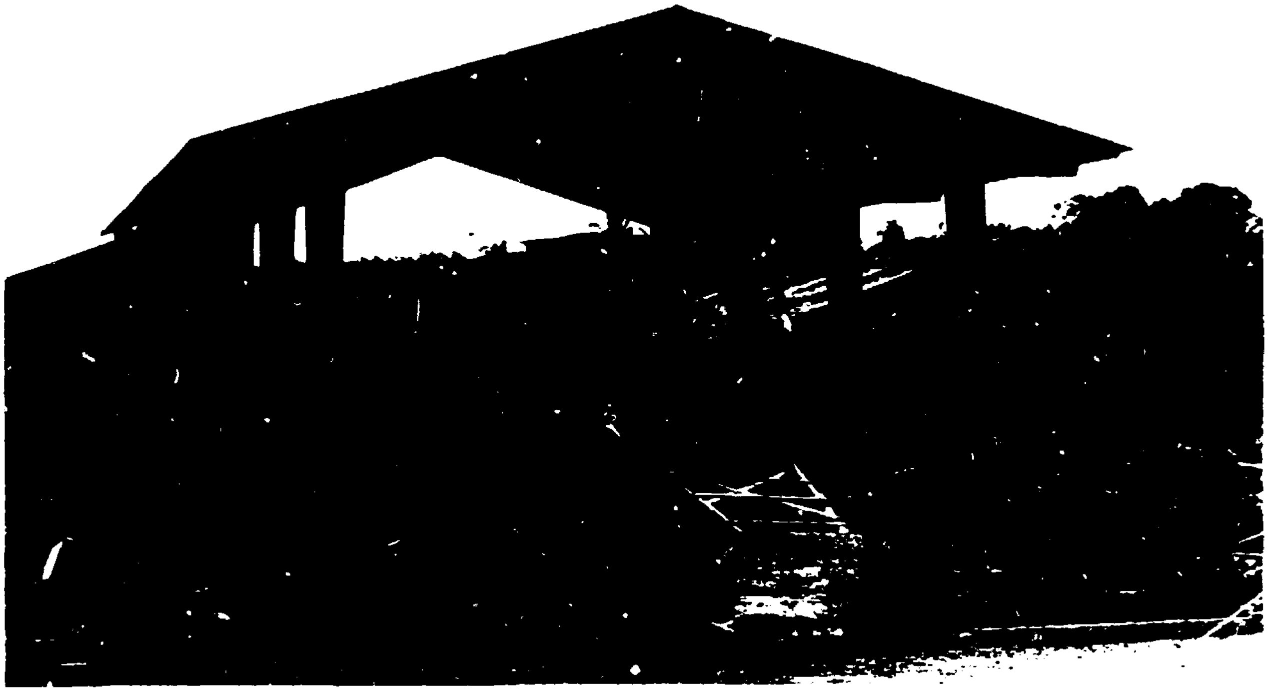

Fig. 1. Lapped-glued portal frame structure

Design

Three hinged arches are statically determinate. Hence, once the reactions at each foot have been calculated from considerations of equilibrium, beinding moments and shear forces can be calculated just as in simply supported beams.

Horizontal and vertical reactions for four common loading conditions are shown in Fig. 2 (see p.4). The symbols used, also terminology, are shown in Fig. 3 (see p.9). Note that these assume that the axis of the leg is vertical. In practice with a tapered leg this is not so, but the error is small, conservative, and may be neglected. By combining these loads, most combinations of dead, live, wind and earthquake loads can be modelled.

The steps in designing a three hinged portal frame are as follows:

1. Determine the live, dead, wind and earthquake loads.

2. Lay out, to a convenient scale, the outside profile from the architectural requirements.

3. Calculate and tabulate the reactions resulting from the various load combinations. From these, determine maximum bending moment and shear force envelopes also direct forces in the legs and across the apex.

4. For the timber stresses allowed, determine the required rafter section at the knee, also the apex and heel depths from shear considerations. The heel should be not less than square and the apex should have a depth to breadth ratio of not less than 1:5.

5. There is no complete analytical method yet discovered of analysing the stresses at the lapped knee joint. However, extensive testing at the Forest Research Institute, Rotorua, New Zealand, has shown that provided the depth to breadth ratio of the rafter is not less than 4, the lapped joint will be stronger than the timber section adjacent to it. The depth of the rafter should not exceed the capacity of the factory's glueing jig and in any case should not be greater than about 24" to limit shear stresses developed due to seasonal swelling and shrinking If a deeper section is required, use a double rafter and treble log, or reduce the frame spacing.

6. For lateral stability, the depth to breadth ratio should not exceed about 6 with rigidly fastened purlins.

7. For the sections thus determined, check bending stresses at other points round the frame, also direct stresses. Combined stress ratios must not exceed unity (see next section).

8. Check the legs for stability as columns. If spacer blocks are glued in at the time the frame is fabricated the legs may be designed according to the rules for spaced columns.

9. Detail the apex connexion for separation under wind uplift, direct force, and shear due to unbalanced or lateral loading. A horizontal pin or tube housed in the frame may be adequate for shear. If not, shear plates may be used to increase the shear capacity of the joint. Shear plates used in end grain may take 60 per cent of perpendicular to grain loading.

10. Detail suitable shoes, bracing, etc.

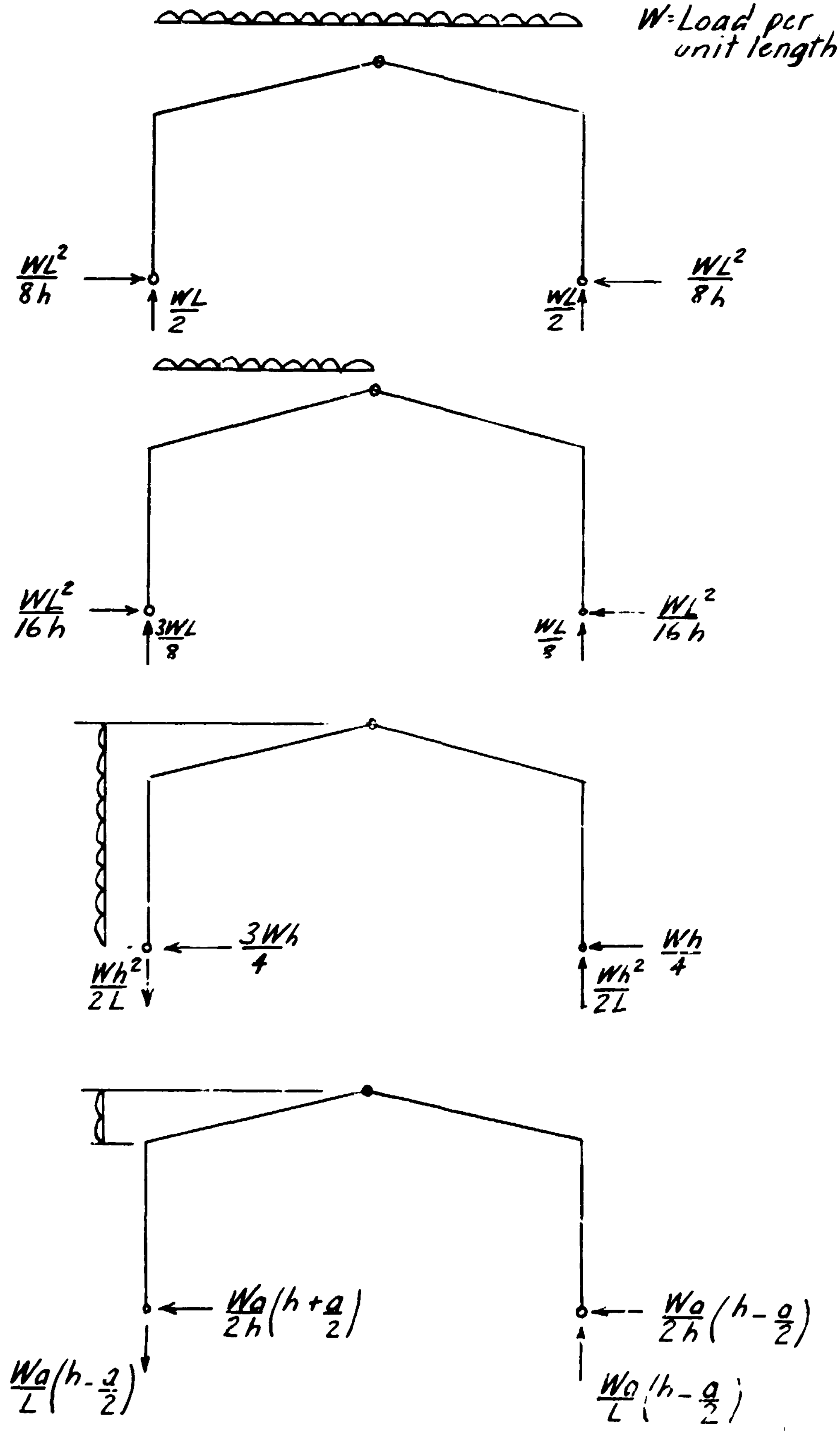

Fig. 2. Horizontal and vertical reactions

Design example

Required: Portal frame structure.

Span 30' Spacing 12'

Height to knee 14' to apex 20'

Loads = DL 6 psf LL* 5psf (includes frame wt)

Wind* windward + 8 psf leeward - 10 psf, normal to roof slope. No walls.

Preliminary: Roof pitch = $\tan^{-1}\left(\frac{20-14}{\frac{30}{2}}\right) = \tan^{-1}\frac{6}{15} = 21.8^\circ$

Reaction convention

Horizontal inwards + ve

Vertical upwards + ve

Moment convention

Tension on inner face + ve

Frame dimensions: $L = 30$, $h = 20$, $a = 6$, $h + \frac{a}{2} = 23$, $h - \frac{a}{2} = 17$

Loads on frame (Assume uniformly distributed)

DL = 6 x 12 = 72 plf

LL = 5 x 12 = 60 plf

WL a vertical down wind[d] = 8 cos 21.8° x 12 = 89 plf

b hor. inwards wind[d] = 8 sin 21.8° x 12 = 36 plf

c vertical up lee[d] =10 cos 21.8° x 12 = -111 plf

d hor. out lee[d] = -10 sin 21.8° x 12 = -45 plf

Assume for tabulation that wind blows from left (L) to right (R)

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* These loads to be determined in accordance with local building code.

Referring to Fig. 2 for reaction coefficients, and tabulating:

Reactions (lb)

Load	Item	H_L	V_L	H_R	V_R
DL	1	405	1080	405	1080
LL full span	2	338	900	338	900
LL 1/2 span L	3	169	675	169	225
WL a	4	250	1001	250	334
b	5	-124	-122	92	122
c	6	-312	-416	-312	-1248
d	7	-115	-230	155	230
4+5+6+7 (total WL)	8	-301	233	185	-562
LL 1/2 span R	9	169	225	169	675
1+2	10	743*	1980*	743	1980*
1+3	11	574	1755	574	1305
1+8	12	102	1303	590	518
11+8 (= 1+3+8)	13	273	1978	759*	743
1+9	14	574	1305	574	1755
14+8	15	273	1538	759	1193
Worst case of 10,12,13,15	16	743	1980	759	1980

Note

As might be expected, DL + LL (full span) has a greater effect than DL + LL (half span) ie 10 > 11 or 13. In fact the only case where 10 does not govern is case 13, which is DL + LL + WL. Notice also that since the net effect of the wind load is rather small, even though one side of the roof is being lifted off, an overall negative i.e. uplift condition does not appear. However this condition does not always apply.

Great care with signs is necessary when determining cases 6 and 7, since the loads are not only the reverse of those shown in Fig. 2, but are also on the opposite side.

A major consideration, not taken into account in the above calculations, is the increase in apparent strength of timber with short duration loads. For wind gust loads, the strength increase factor is 2, and design stresses for loads due solely to wind (or earthquake) may be doubled. In practice, the simplest way to take this into account is to divide the various load components by the appropriate duration of load increase factors, and use the same design stresses throughout. If this had been done in the above case, the worst design case would be simply DL + full LL.

For glulam of F 11, 25 mm (1") lamination thickness L 2 grade, stress increase factor = 1.15

F_b = 1594 x 1.15 = 1833 psi

F_t = 1246 psi

F_s = 150 psi

F_c = 1202 psi

E = 1.52×10^6 psi (quoted from AS 1720 - converted to Imperial units)

M max. at knee = 743 x 14 x 12 lb in = 124824 lb in

Z req^d = $\frac{124824}{1833}$ = 68 in^3

For 4" thickness, $68 = \frac{4\,d^2}{6}$ $\quad d^2 = 68 \times \frac{6}{4}$ $\quad$ d = 10"

This falls outside the $\frac{d}{b}$ rules given on page 3.

Try 3" $\quad d^2 = 68 \times \frac{6}{2.75}$ $\quad$ d = 11.66 say 12" OK

For finished ex. 3" timber, b = 2.75" $\quad d^2 = 68 \times \frac{6}{2.75}$ $\quad$ d = 12.18

Make knee depth 13", apex depth 3" x 1.5 - say 6"

For leg, try 2 ex 4" thick - say 1 1/2" finished

Total leg width = 2 x 1.5" + 2.75" = 5.75" - say 6"

Make leg depth at foot = 6"

Check shear at foot

$$f_s = \frac{3}{2} \times \frac{743}{6 \times 3} = 62 \text{ psi OK}$$

Check direct compression at foot

$$f_c = \frac{1980}{6x2x1.5} = 110 \text{ psi OK}$$

Check column strength - spaced column

$$\frac{l}{d} = \frac{14' \times 12}{1.5"} = 112 \text{ - exceeds 80 NG} \qquad d \text{ min} = \frac{14x12}{80} = 2.1"$$

Therefore, make leg same thickness as rafter, i.e. 2.75"

$$\frac{l}{d} = \frac{14\text{x}12}{2.75} = 61 \quad \text{OK}$$

For glued spacer blocks at ends, within $\frac{1}{20}$

$$F_c' = \frac{0.75\ E}{(\frac{l}{d})^2} = \frac{0.75 \times 1.52 \times 10^6}{61^2} = 306$$

Area A at mid height $= \frac{6+13}{2} \times 2 \times 2.75\ \text{in}^2 = 52.25\ \text{in}^2$

$$F_c' = \frac{1980}{52.25} = 38\ \text{psi} \quad - \text{OK}$$

Note: In order to maintain foot of frame at least square, depth = 3 x 2.75" = 8.25". Stresses will therefore be reduced from above levels.

Shear at apex. Worst use is unbalanced LL - case 3

$$V = 225$$

$$f_v = \frac{3}{2} \times \frac{225}{6\text{x}3} = 18.75\ \text{psi} \quad \text{OK}$$

Combined stresses at mid height of leg

$b = 2 \times 2.75" = 5.5"$ $d = \frac{8.25 + 13}{2} = 10.6"$

$$M = \frac{124824}{2}\ \text{lb in} = 62412\ \text{lb in}$$

$$f_b = \frac{62412 \times 6}{5.5 \times 10.6^2} = 606\ \text{psi}$$

$$\frac{f_b}{F_b} = \frac{606}{1833} = 0.330$$

$$f_c = \frac{1980}{5.5 \times 10.6} = 34\ \text{psi}$$

$$\frac{f_c}{F_c} = \frac{34}{306} = 0.111$$

$$0.330 + 0.111 = 0.441 < 1 \qquad \text{OK}$$

Check on positive bending stresses in rafter near apex.

h' = distance vertically from apex to rafter ℄

l' = distance from vertical ℄ through apex

d = rafter depth = $6 + \frac{13 - 6}{15} \times l'$

M = bending moment

l'	h'	12h'H	$-12(72+60)\frac{l'^2}{2}$	M	d
o	o	o	o	o	6
1	.38	3387	-792	2595	6.46
1.5	.57	5082	-1782	3300	6.70
2	.76	6774	-3168	3606	6.93
2.5	.95	8470	-4950	3520	7.17
3	1.14	10161	-7128	3033	7.40
4	1.52	13547	12672	875	7.87

At M max, $f = \frac{3606 \times 6}{2.75 \times 6.93^2} = 164$ psi OK

The remainder of the design is merely detailing of shoes and apex connections according to whatever steel is conveniently available.

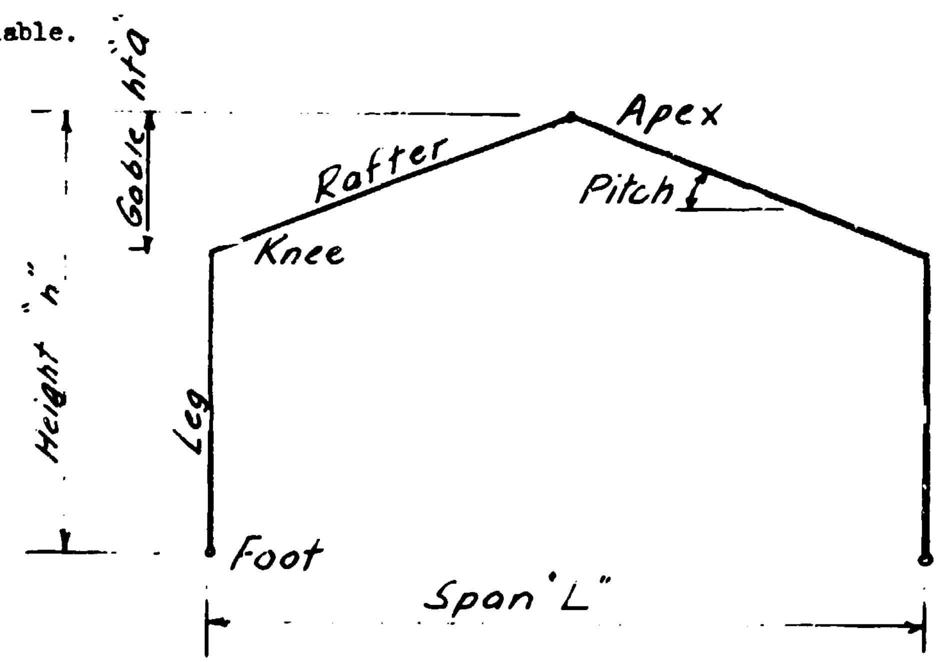

Fig. 3. Portal frame terms

Effect of taper

The tapered cut, where the end grain of the laminates is exposed should be placed on the inside of the frame so that it is in compression under normal loads. In a tapered beam, the stresses interact and shear stress does not necessarily have a parabolic distribution across the beam section.

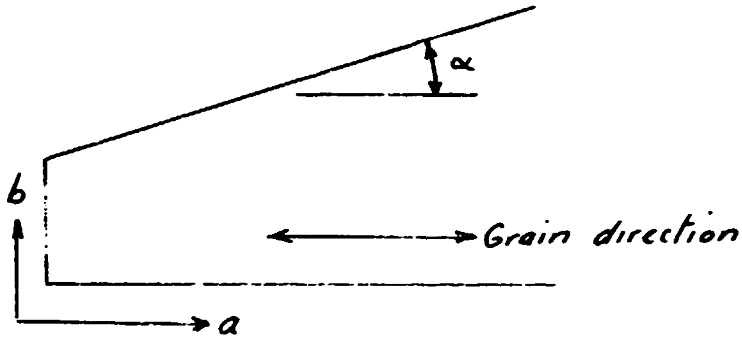

Fig. 4. Tapered beam section

If f_a = actual tension or compression stress parallel to grain

f_b = actual tension or compression stress perpendicular to grain

f_{ab} = actual shear stress

F_a = allowable tension or compression stress parallel to grain

F_b = allowable tension or compression stress perpendicular to grain

F_{ab} = allowable shear stress

then

$$\frac{f_a^2}{F_a} + \frac{f_b^2}{F_b^2} + \frac{fab^2}{Fab^2} = 1$$

In tapered members at the tapered face

$$f_a = f_{ab}\cot\alpha \ , \ f_b = f_{ab}\tan\alpha$$

so

$$\frac{f_a^2}{F_a^2} + \frac{f_a^2 \tan^2\alpha}{F_{ab}} + \frac{f_a \tan^4\alpha}{F_b^2} = 1$$

Solving for f_a,

$$f_a^2 \left(\frac{1}{F_a^2} + \frac{1}{F_{ab}^2}\tan^2\alpha + \frac{1}{F_b^2}\tan^4\alpha\right) = 1$$

$$\frac{1}{F_a^2} + \frac{1}{F_{ab}^2}\tan^2\alpha + \frac{1}{F_b^2}\tan^4\alpha = \frac{1}{f_a^2}$$

Let $f_a = KF_a$ (K is a function of the material properties and the slope of the taper)

Then $$\frac{1}{K^2F_a^2} = \frac{1}{F^2} + \frac{1}{F_{ab}^2}\tan^2\alpha + \frac{1}{F_b^2}\tan^4\alpha$$

$$\frac{1}{K^2} = 1 + \left(\frac{F_a}{F_{ab}}\right)^2 \tan^2\alpha + \left(\frac{F_a}{F_b}\right)^2 \tan^4\alpha$$

$$K = \left[1 + \left(\frac{F_a}{F_{ab}}\right)^2 \tan^2\alpha + \left(\frac{F_a}{F_b}\right)^2 \tan^4\alpha\right]^{-0.5}$$

For the various combinations of allowable (design code) stresses, K. may be calculated for particular tapers. For example for SD7 and F11 timber, and a slope of 1 in 10 = 0.1,

F_a = 8.6 MPa

F_b = 3.3 MPa (compression)

F_{ab} = 1.05 MP_a

$$K = \left[1 + \left(\frac{8.6}{1.05}\right)^2 \times 0.1^2 + \left(\frac{8.6}{3.3}\right)^2 \times 0.1^4\right]^{-0.5}$$

= 0.7735

f_a = 0.7735 x 8.6 MPa

= 6.65 MP_a

Note that this is for compression on the tapered edge. For tension across the grain no code stress is normally assigned, but in this case a value of $\frac{Fab}{3}$ may be used for F_b (tension).

The frame should be checked against the interaction at points of maximum positive bending moment under normal, i.e., live plus dead, and also under uplift conditions.

2. FABRICATION OF GLUED KNEE PORTAL FRAMES

Glueing jig

An accurate jig capable of applying sufficient clamping force is required. A suitable jig is shown in Fig. 5. General details are: Size : about 24" (60 cm) square x 1" (25 mm) thick.

Clamping rods: 1" (25 cm) diameter 30" (75 cm) long, screwed into threaded holes in the base, and with 10" (20 cm) of thread at the top. These must be accurately perpendicular to the base, particularly the central one.

Note the lifting handles on the top clamp plate.

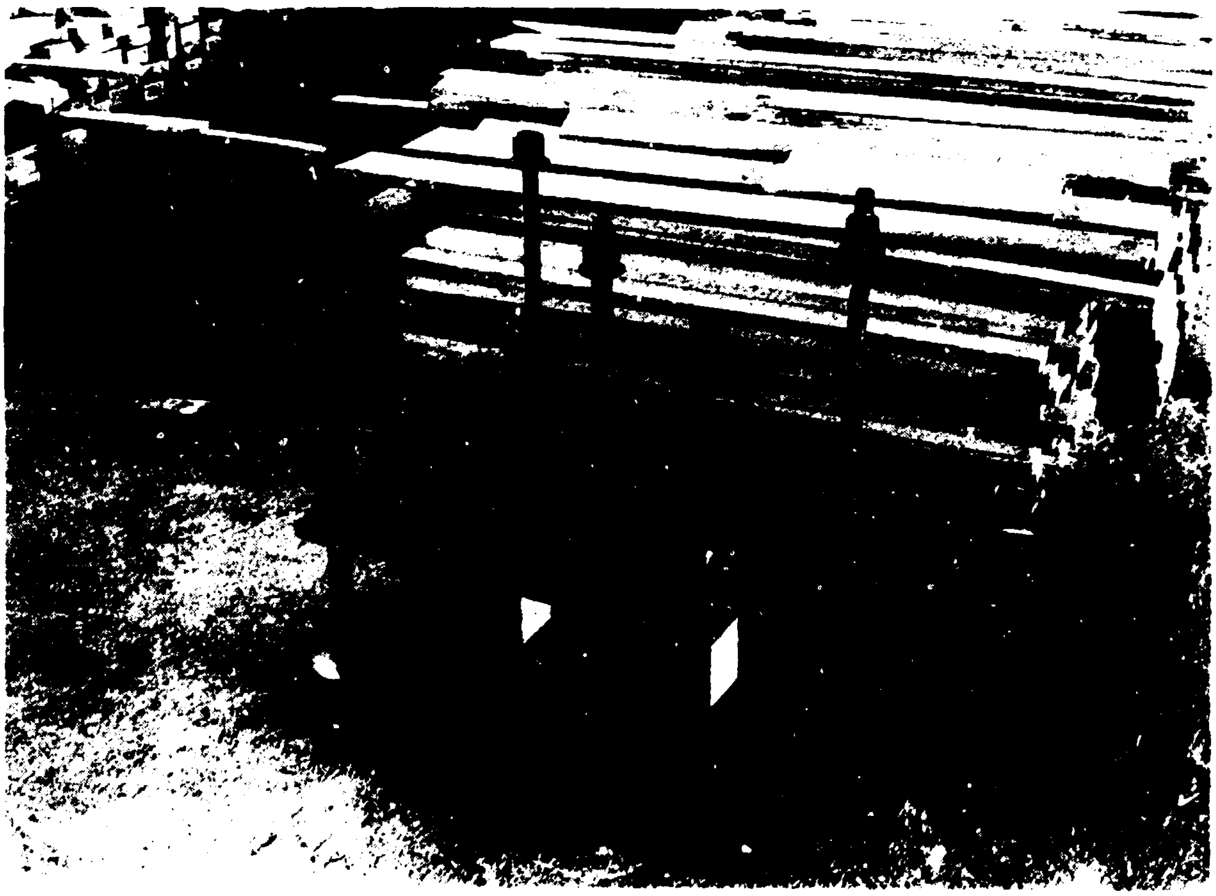

Fig. 5. Portal frame jig

Component Manufacture

Legs and rafters are usually tapered. Two components can therefore be cut from a parallel sided beam. Because of the exposure of central laminations on the tapered face, laminations throughout the beam must be of uniform grade and quality.

The beam width must allow for the following:

Leg or rafter maximum width

Plus width at small end

Plus saw kerf

Plus planing allowance

The tapered cut is best done by power hand circular saw or chain saw. In most cases it should be planed after sawing, since it is the tapered face which is exposed to view. The saw cut can be marked out by snapping a chalk line onto the face of the beam. This is then pencilled over.

The hole for the central clamping rod should pass through the centre of area of the lap. In components which approach the dimensions of the jig the clearance for the other clamping rods should be checked with a template of the jig made of plywood or hardboard. The position of the hole may have to be adjusted slightly in these cases. The centre of area may be determined by cutting a pattern of the lap from cardboard and balancing this over a stick on two axes. This pattern will be required for marking out the glued areas.

The holes for the centre clamping bolt should be accurately drilled, using the above pattern for marking out. After drilling the first rafter and first leg, a trial assembly should be performed to check clamping bolt clearances.

At the same time that the centre hole is marked out the extent of the lap should be marked on the components. Remember that in doubled units there will be a left and a right hand component. These marks will show the extent of the area to be glued. In architectural work, the surfaces adjacent to the glue area should be masked off about 1/4" (5 mm) outside the lines, to protect the exposed surface from excess glue. This also applies to the edges of members next to the glued areas. It is very difficult to clean up glue afterwards, particularly in between doubled areas.

The positions of spacer blocks should be marked at this stage and masked off if necessary.

Setting Up

A dry assembly should be performed. With light components, the weight of the jig will keep it in position, but with heavy components there is a danger of it being knocked out of position and the jig should be bolted to the floor. Calculate the distance from top of apex to outside of foot, and adjust the leg and rafter to this, using a steel tape. Set up vertical stops near the apex and foot. The leg of a heavy bench is suitable for this purpose.

Glueing and Clamping

Ensure that surfaces to be glued are clean and free of dust by brushing with a stiff bristle brush. Double spread mating surfaces using hand roller or brush. Lay up the frames in the jig as shown in Fig. 6. Depending on overall thickness, 2 to 4 half frames can be clamped simultaneously. After placing the cover plate on the jig, torque down the clamping nuts to give a glueing pressure of about 150 p.s.i. (1000 kPa). After about 10 minutes, re-torque, since squeeze-out may lower the pressure. See Fig. 6.

Spacer blocks may be clamped using bolts from the beam jig and pull-down bars. If this is done, the bottom plate of the jig will have to be packed up level with the upper face of the bottom pull-down bar.

Fig. 6. Clamping up a glued joint portal frame with pneumatic impact wrench

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