OLD GROWTH: OUR TIMBER ENGINEERING HERITAGE

Hank Bier, Technical Editor

For this issue, of Old Growth the original article was published in "The Timber Development Association Bulletin" Vol 1 No. 16, November 1964. "Design notes for plywood folded plate roofs" by T M Wardle, an engineer with the then Utilisation Development Division of the NZ Forest Service was part of the inspiration for a couple of roof structures later designed for the Forest Service. I did one for a two storey office that was built in 1977 for the Tapawera headquarters in the Nelson region. This was featured on the cover of the loose plywood chapter in the first "Timber Use Manual" and is still in the plywood chapter of what became the "Timber Design Guide". That building had an upper level roof span of about 13.5 meters. The trick was to convince the builder that a slender piece of glulam chord could span the distance, not as a beam, but as a tension element.

Please note that the techniques/technologies referred to in this paper (the papers reproduced in the Old Growth column) are historic and do not reflect current practice.

DESIGN NOTES FOR PLYWOOD FOLDED-PLATE ROOFS

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The folded-plate roof has become a familiar feature of contemporary architecture. The original folded-p1ate structures were built in concrete, but plywood has been used successfully for this purpose since about 1954. The lack of data on New Zealand made plywood has restricted the progress of plywood folded-plate design in this country; but, with the impending publication of industry standards for structural-grade plywood manufactured specifically for use in highly stressed structures, further development is now feasible. It should be noted that the ordinary interior and exterior grades of plywood are not designed .for structural use; such grades are built for appearance, and the strength characteristics are largely uncontrolled.

Folded-plate roofs add to the architectural value of a building, and in addition have economic advantages: large areas of column-free space are possible; roof overhangs may be cantilevered out to form veranda roofs. When built in plywood, a folding plate is a light but stiff form of roofing capable of carrying all normal roof loads.

A plywood folded plate is a structural component consisting of a number of diaphragms made of plywood skin and sawn timber frame connected to form a series of vee beams. Terminology and construction details are illustrated in Figure 1. Folded plates can be used in the form of a single inverted vee, termed a "single fold," or in the form of a number of vees, termed a "multiple fold". Ties are required at the ends of the vee to carry the horizontal thrust. The fastenings of the plywood sheathing to the framing members must be of sufficient strength to ensure structural interaction of the members.

The plywood sheathing may be nailed, nail-glued or pressure-glued to the sawn-timber rafters, blocking, ridge chords and valley chords. Gluing of the joints is particularly suitable for shop prefabrication and will result in a stiffer structure than nailing. Note that the splices in ridge and valley chords should also be glued if full advantage is to be taken of the additional stiffness of a glued construction. Nailed joints have the advantage of being easier to make in the field. If an interior lining is applied, insulation may be installed between the lining and the sheathing. If the lining is structural plywood correctly fastened to the frames, both skins may be calculated to act with the framing as a stressed-skin construction. The plywood plate will require a protective

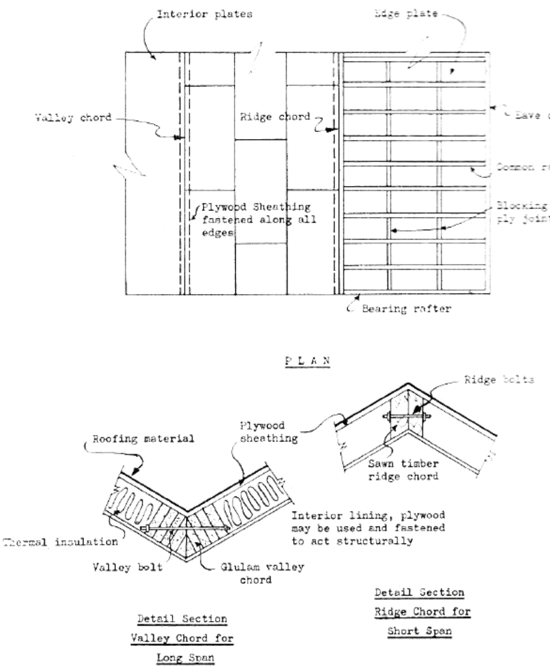

Figure 1. Folded-Plate construction detail.

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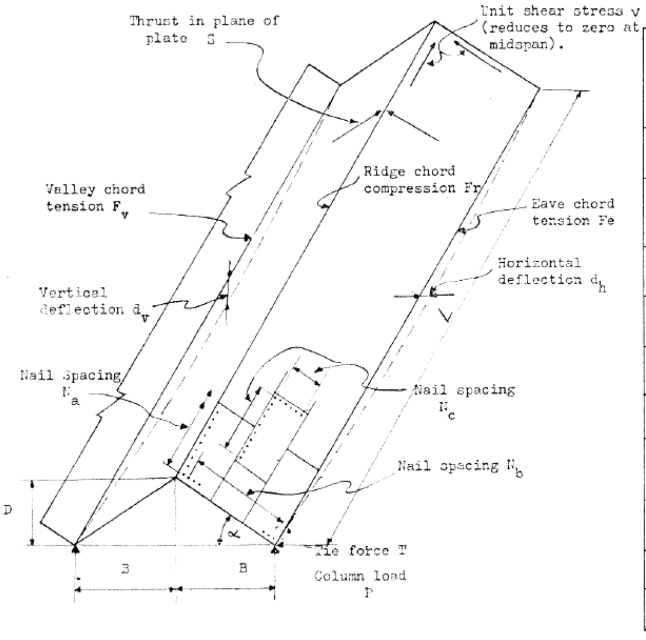

	MULTIPLE FOLD		SINGLE FOLD
	Interior Plate	Edge Plate	
Ridge Chord Compression Fr	$\frac{wBL^2}{4D}$	$\frac{3wBL^2}{16D}$	$\frac{wBL^2}{8D}$
Valley or eave chord tension Fv	$Fv = \frac{wBL^2}{4D}$	$Fe = \frac{w\,BL^2}{16D}$	
Column loads P	wBL	$\frac{wBL}{4}$ if eave supported on wall $\frac{wBL}{2}$ if eave supported on beam	
Max. unit shear Stress v	$\frac{wBL}{2D}$	$\frac{wBL}{4D}$	
Thrust in Plane of plate S	$\frac{wB}{2\sin\alpha}$		
Nail Spacing Ply to chords Na	$\frac{12r}{\sqrt{v^2+S^2}}$	$\frac{12r}{v}$	
Ply to bearing rafter Nb	$\frac{12r}{v\ max.}$		
Ply to common rafters and blocking Nc	$\frac{18r}{v}$ for 3 or more courses of ply $\frac{12r}{v}$ for less than 3 courses		
Tie force T	$\frac{wB^2L}{43}$		
Ridge and valley deflection dv	$\frac{\Delta}{\sin\alpha}$		
Eave deflection d_h		$\frac{\Delta}{\cos\alpha}$	

$$\Delta = \frac{5vL^3\cos\alpha}{8EAB} + \frac{vL}{4Gt} + 0.094Le_n$$

Figure 2

Figure 2. Forces in a simple span Folded-Plate roof under uniformly distributed live load.

roof covering from the weather. Sheet metal, built-up bituminous felt roofing, fibreglass, and synthetic elastomers have all been used as roofing materials for folded-plate roofs. We appear to be at the beginning of a new era in roofing, and the next few years should see much development of materials suitable for roof coverings such as neoprene, chlorosulfonated polyethylene (hypalon), polyvinyl fluoride (tedlar), polyvinyl chloride, epoxies, butyl rubber, butyl latex, and polyisobutylene.

STRUCTURAL ACTION

The basic difference between the structural action of a folded-plate roof and an ordinary pitched roof is that in the latter the roof sheathing cannot transmit shear. Thus, when a vertical load is applied to a conventional pitched roof, the thrusts induced in the rafters must be resisted by the supporting walls or by cross ties. In a plywood folded plate, the plywood sheathing acts as a web to transmit shear. The forces in the plane of the plate are thus transferred to the ends of the plate, where the vertical component is carried by columns and the horizontal component by ties.

The analysis of folded-plate roofs may be made by considering the structure as a series of vee-section beams carrying the vertical load. The vee section acts about an axis midway between the chords. A similar result is obtained by resolving the vertical loads into components parallel and normal to the plane of the roof surface. The components are resisted by slab action, with the rafters spanning between the ridge and eave and by plate action, with the roof plate spanning the full length of the roof.

DESIGN OUTLINE

An outline of the design method for a simple span, uniformly loaded, folded-plate roof is given. The forces and derived expressions are illustrated in Figure 2.

RAFTERS

The spacing of common rafters will be governed by the load-carrying capacity of the plywood and the length of the plywood sheet. If the standard eight-foot sheet is used, the rafter spacing will be 12in., 16in., or 24in. The rafter is designed to carry the component of load normal to the roof surface and is considered as a simple span between ridge and eave centrelines. Often the rafter is designed to act, in conjunction with the plywood, as a stressed-skin panel [4]. The bearing rafter at the ends of the span carries bending loads from the plywood, and, in addition, transmits the shear force from the plate to the tie and columns. The shear force creates an axial load in the bearing rafter varying from zero at the ridge to a maximum at the eave. The connection of the rafters to the ridge and eave chords must be detailed to transmit the rafter shear forces. The rafters act as splice plates between adjacent sheets of plywood. and the rafter width may be governed by the width required to prevent splitting during nailing of the sheets.

In the case of a bearing rafter supported by end bearing on a valley chord, the bearing stress perpendicular to the grain of the chord may govern the rafter dimensions. Rafters also act to stiffen the plywood web against shear buckling, and occasionally rafter spacing may depend upon this function.

CHORDS

The bending ,moment to be resisted is calculated for the span of the roof and for the end support conditions, simple support, cantilevered overhangs, or continuous spans. The chord force at any section can be computed by dividing the bending moment at the section by the lever arm of the chord force couple.

For the forces of ridge and valley chords of a simple span interior plate, the moment is $M = WL/8 = (2wBL)L/8 = wBL^2/4$ which is equated to the chord force couple $M = FD$. Solving for chord force $F = wBL^2/4\ D$.

Similarly, from a consideration of the roof area supported, the chord force at the exterior ridge of a multiple-fold roof is derived as $F = 3wBL^2/l6D$. The force in the ridge chord of a single-fold roof is $F = wBL^2/8D$. In both single-fold and multiple-fold roofs, the eave force is $F = wBL^2/l6D$.

For a given unit load and plate span, the chord force F varies as the ratio B/D, i.e., the tangent of the slope. Thus, for a given slope, the chord force does not change with increased plate width.

The chord members must be spliced to run the full length of the span. For sawn-timber chords, the number of splices will be governed by the available lengths of timber. Laminated chords can be produced in lengths suitable for handling and erection.

SHEAR

Considering the end fold of a multi-fold plate, the vertical load at the ridge is $WB/2$ from each plate. This load causes a thrust in the plane of the plates $S = wB/2\ sin_\alpha$ lb/ft uniformly along the ridge. The thrust is resisted by the beam action of the plate. The maximum unit shear stress caused by the thrust, assuming the plate to be simply supported, is:

$$v = \frac{SL}{2B \div \cos\alpha} = \frac{wBL}{4\sin\alpha} \times \frac{\cos\alpha}{B} = \frac{wBL}{4D} lb / ft$$

The shear force decreases from a maximum at the support to zero at midspan.

An interior plate supports half the load from the two adjacent plates, therefore the total load is twice for an edge plate and the maximum unit shear stress becomes $v = wBL/2D$ lb/ft.

The thickness of plywood required to carry the shear is:

$$t = \frac{v\ \max}{12 \times allowable \quad shear \quad stress}$$

For an interior plate:

$$t = \frac{wBL}{48\,D \times allowable \quad shear \quad stress}$$

For an edge plate:

$$t = \frac{wBL}{24\,D \times allowable \quad shear \quad stress}$$

NAILING

For folded-plate action to take place, the plywood web must be connected to transmit shear from the chords and across web joints. If nail construction is used the number of nails required is found from the unit shear stress at the section divided by the allowable bearing value of the nail. In areas of low shear stress, the nail spacing will be governed by the requirement to prevent buckling and to attach the plywood firmly. Maximum nail spacing should not exceed 6 in. at the panel to chord connections and 72 in. at other plywood joints.

At the bearing rafter, the maximum unit shear stress must be transferred into the rafter.

The number of nails per foot = $v\ max/r$ and nail spacing = $N_b = 12r/v\ max$. This will also hold for the chord nailing at the eaves.

For chord nailing at ridges and valleys, there is an additional force at right-angles to the chord caused by the thrust S. Combining the two forces vectorially, the nail spacing becomes:

$$N\alpha = \frac{12}{\sqrt{v^2 + S^2}}$$

Alternatively, the thrust S may be carried by specially designed rafter-to-chord connections and the effect on the nails ignored. The S force causes a tension component normal to the direction of the valley and the splitting of the valley chord should be checked and bolts provided to resist the tension.

For shear transfer between plywood sheets, the nail spacing is calculated as before, $N_c = 12r/v$. The spacing can be increased by 50% to $N_c = 18r/v$, where there are three or more plywood sheets in the width of the plate.

If glue construction is used, the glue area should be checked against the unit shear stress using the allowable rolling shear values for the plywood. Note that the accepted approximate methods of calculating - the strength of plywood [3] reduce the allowable rolling shear stress - in the edge joint of a framed panel by 50%.

TIE RODS

For uniform load on interior plates, the plate shear forces acting axially on the bearing rafter will balance out, and no tie rods are required. However, for edge plates or for non-uniform loading of interior plates, there are unbalanced forces in the bearing rafters which must be resisted by horizontal ties. It can be shown that the edge-plate thrust is greater than the effect of the unsymmetrically loaded interior panels.

For design purposes, the tie force can be taken as that due to an edge plate $T = \frac{1}{2}\ Vmax.\ \cos\alpha$. In the case of a simply supported span, substituting for *Vmax* will give $T = \frac{1}{2}(wBL) \cos\alpha/(2 \sin\alpha) = wB^2L/4D$ lb. For cantilevered construction or continuous spans, the tie force will increase. Ties may be steel rods or timber members. The junction of the tie, bearing rafter, and column should be detailed to avoid secondary stresses due to non-coincidence of tie, rafter and column forces.

DEFLECTION

The deflected form of interior and edge plates is shown in Figure 3. In an interior panel, the net movement will be vertical, and in an edge panel supported on a wall, the movement will be horizontal only. Deflection in the plane of the plate is calculated as for a plywood diaphragm loaded on edge.

$$\Delta = \frac{5v \max .L^3 \cos\alpha}{8EAB} + \frac{vL}{4Gt} + 0.094\, Le_n$$

To which should be added an allowance for joint slip in the chord splices if these members are mechanically fastened. For the origin of this formula, see reference 1.

In a glued structure, the nail factor 0.094 Le_n is omitted. The vertical deflection for an interior ridge valley is $d_v = \Delta/\sin\alpha$. For an eave supported by a wall, the vertical deflection is zero and the horizontal deflection is $d_h = \Delta/\cos\alpha$. If the eave rests on a beam, the vertical deflection of the beam should be checked.

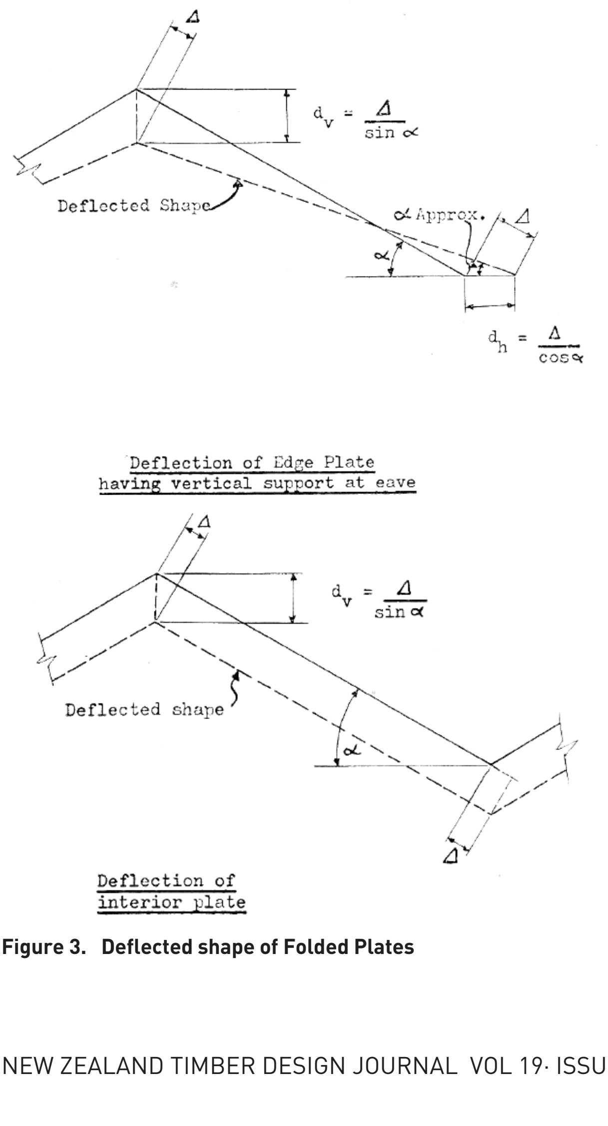

Figure 3. Deflected shape of Folded Plates

WIND AND SNOW LOAD

Where snow loading is to be provided for, the designer should bear in mind that snow may pile up in the valleys and impose snow loads greater than normally allowed for a flat roof. Ice build-up in the valleys could also impose a horizontal force on the plates and increase the tension normal to the valley chords. The possibility of this latter condition is fairly remote and would be of short duration.

Experience with load tests [2] shows that wind loads at right-angles to the ridge line are resisted principally by the windward edge plate. It is customary to design edge plates to carry all wind forces and to ignore the resistance of all interior plates. Where overhangs are used, high winds can cause appreciable uplift and careful attention must be given to the provision of adequate hold-downs.

PROPORTIONING

For economy, it is desirable to make the height of the fold about one-twelfth of the span, with a lower limit of one-fifteenth span. The flatter the pitch of the plate the smaller the area of roofing material becomes, but the chord forces and shears increase. Chord force and shear increase more rapidly as pitch drops below about 6 in 12. The economic range appears to be between 6 in 12 and 8 in 12 in North America, but it is recommended that an economic analysis be made for New Zealand material and labour-cost conditions.

Details of construction will be the subject of a future design note, but, very briefly, those details requiring special attention are as follows:

(1) The tie to bearing rafter should be detailed to avoid secondary moments due to eccentricity of applied loads.

(2) The rafter to chord connections must be capable of transmitting shear from rafters. If the connections can also transmit the thrust force *S*, then savings in the plywood to chord nailing are possible.

(3) Camber against dead load deflection plus part of live load deflection should be provided. For field constructed plates, the chords can be propped to the required camber and the propping struck after the roof is complete. For shop fabricated panels, the camber can be built in during fabrication.

(4) For prefabricated panels having two skins, access holes must be detailed for installation of bolts during erection.

(5) Chord splices require careful detailing, and two piece valley chords must be fastened together at intervals to resist tension normal to the chord.

NOMENCLATURE

L - Span of the folded plate.

B - Horizontal distance from centre line of ridge to centre line of valley.

D - Vertical distance centre to centre of chords in feet. For wide plates it is sufficiently accurate to use the vertical projection of the plywood plate.

α - Slope of roof angle.

T - Tie force (lb) .

P - Vertical reaction on columns (lb).

F_R - Ridge force (1b).

F_v, F_E - Valley or eave force (1b).

V - Total shear force in the plane of the plate (1b).

v - Unit plate shear (lb/ft).

w - Applied loading on horizontal projection (lb/sq.ft).

W - Total load on plate (lb.).

S - Thrust acting perpendicular to the chords in the plane of the plate (lb/ft).

t - Plywood thickness (in.) .

A - Area of chord in square inches.

E - Modulus of Elasticity of plywood.

G - Modulus of Rigidity of plywood.

r - Allowable lateral bearing force for nails (lb/nail).

e_n - Nail deformation under design load, inches.

REFERENCES AND SUGGESTIONS FOR FURTHER READING

[1] *Plywood, Properties, Design, and Construction, Chapters 7 and 8*; N. S. Perkins, 1962. Douglas Fir Plywood Association.

[2] *Design of Plywood Folded Plates*; D. H. Brown. Forest Products Journal, April, 1963.

[3] *Plywood Design Fundamentals*. Plywood Manufacturers of British Columbia.

[4] *Single-fold Plywood Folded Plates*. Plywood Manufacturers of British Columbia.