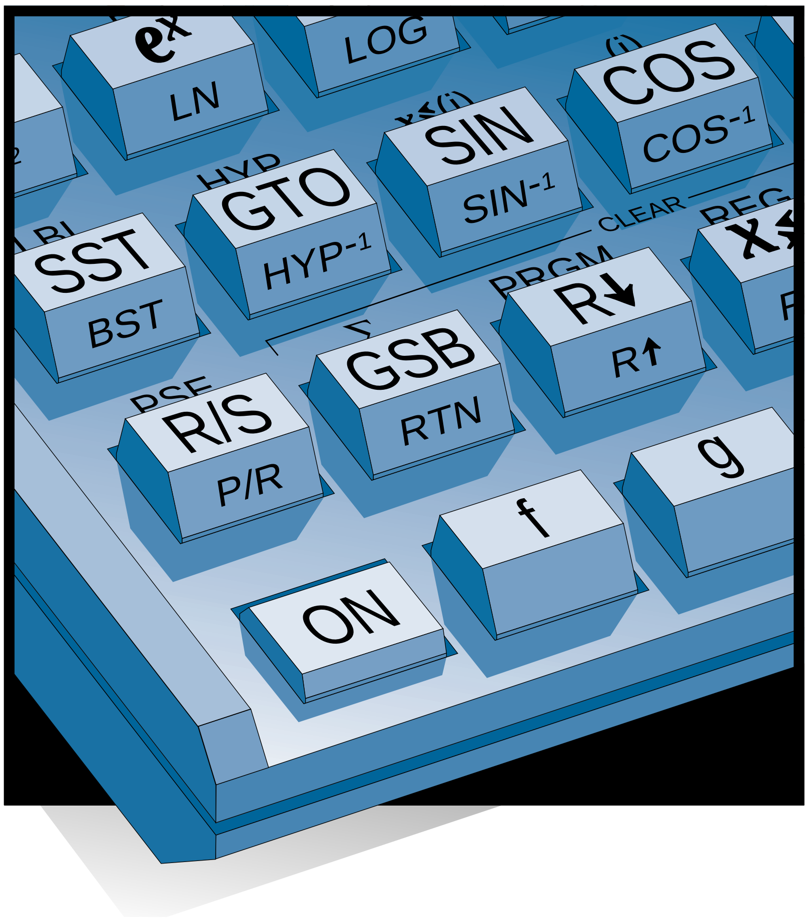
SUPPLEMENT 1

Design And Fabrication Of Plywood Curved Panels

March 1990



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Wood is good. It is the earth's natural, energy efficient and renewable building material.

Engineered wood is a better use of wood. It uses less wood to make more wood products.

That's why using APA trademarked I-joists, glued laminated timbers, laminated veneer lumber, plywood and oriented strand board is the right thing to do.

A few facts about wood.

- *We're not running out of trees.* One-third of the United States land base – 731 million acres – is covered by forests. About two-thirds of that 731 million acres is suitable for repeated planting and harvesting of timber. But only about half of the land suitable for growing timber is open to logging. Most of that harvestable acreage also is open to other uses, such as camping, hiking, hunting, etc.

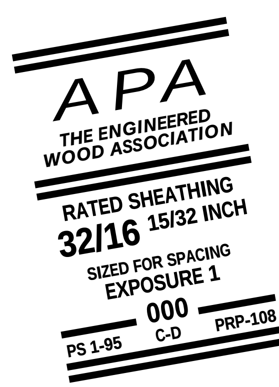
- *We're growing more wood every day.* American landowners plant more than two billion trees every year. In addition, millions of trees seed naturally. The forest products industry, which comprises about 15 percent of forestland ownership, is responsible for 41 percent of replanted forest acreage. That works out to more than one billion trees a year, or about three million trees planted every day. This high rate of replanting accounts for the fact that each year, 27 percent more timber is grown than is harvested.

- *Manufacturing wood products is energy efficient.* Wood products made up 47 percent of all industrial raw materials manufactured in the United States, yet consumed only 4 percent of the energy needed to manufacture all industrial raw materials, according to a 1987 study.

Material	Percent of Production	Percent of Energy Use
Wood	47	4
Steel	23	48
Aluminum	2	8

- *Good news for a healthy planet.* For every ton of wood grown, a young forest produces 1.07 tons of oxygen and absorbs 1.47 tons of carbon dioxide.

Wood. It's the right product for the environment.



NOTICE:
The recommendations in this report apply only to panels that bear the APA trademark. Only panels bearing the APA trademark are subject to the Association's quality auditing program.

Foreword

This publication presents the recommended method for the design and fabrication of curved plywood roof panels spanning between load-bearing supports so that the stresses developed act circumferentially around the curve.

Working stresses and other design criteria are given in the PLYWOOD DESIGN SPECIFICATION, abbreviated PDS.

This recommended design method is based on standard engineering formulas, and was confirmed by tests recorded in APA Laboratory Report No. 77, PLYWOOD ARCH PANELS.

This method does not cover the special requirements for design of "vaults," which span parallel to the axis of the arch, and produce stresses at right angles to those in simply supported arches. Nor does it cover design of inverted curved panels, which require special consideration in design for concentrated loads. Such inverted panels are probably best designed as skins supported on curved beams.

Presentation of this design method is not intended to preclude further development. Where adequate test data are available, therefore, the design provisions may be appropriately modified. If they are modified, any such change should be noted when referring to this publication.

The plywood use recommendations contained in this publication are based on APA's continuing program of laboratory testing, product research and comprehensive field experience. However, there are wide variations in quality of workmanship and in the conditions under which plywood is used. Because the Association has no control over those elements, it cannot accept responsibility for plywood performance or designs as actually constructed.

Technical Services Division
APA

A Word on Components

Plywood-lumber components are structural members which depend on the glued joints to integrate the separate pieces into an efficient unit capable of carrying the design loads.

Materials in these components may be stressed to an appreciably higher level than in nonengineered construction.

Since improperly designed or fabricated components could constitute a hazard to life and property, it is strongly recommended that components be designed by qualified architects or engineers, using recognized design and fabrication methods, and that adequate quality control be maintained during manufacture.

To be sure that such quality control has been carefully maintained, we recommend the services of an independent testing agency. A requirement that each unit bear the trademark of an approved agency will assure adequate independent inspection.

Contents – Design and Fabrication of Plywood Curved Panels

List of Symbols and *Location*

A_{II} = Tabulated area of material with grain parallel to stress in arch cross section (in.^{2} per foot of width) i
Part 1, Section 3.3.1.6, Appendix, Section A2.3 and Table in PDS Supplement 3, Section 3

a = Factor for calculating H *Figure 3.3.1.1*

b = Width of rib for spaced-rib panel (inches); width of glued strip for strip-glued solid-core panel (inches); or 12″ *Part 1, Sections 3.1.3 and 3.3.1.7.1*

b_c = Width of core for full panel (inches)
Part 1, Section 3.3.1.7.2

C_{cr} = Calculated critical skin buckling stress (psi)
Part 1, Section 3.1.2.2

c = Distance from panel-assembly neutral axis to extreme outer fiber (inches)
Appendix, Section A2.5

E = Tabulated modulus of elasticity of plywood (psi)
Part 1, Sections 3.1.2.2 and 3.3.19 and PDS Table 3

E_c = Modulus of elasticity of core in compression (psi)
Part 1, Section 3.1.2.2 and Part 2, Section 3.2.3

F_c = Tabulated compression in the plane of the plies-parallel or perpendicular to the face grain. (psi)
PDS Table 3

F_c' = Allowable compression in the plane with adjustments (psi)
Appendix, Section A2.4

F_r' = Allowable radial stress including adjustments (psi)
Appendix, Section A2.4 and PDS, Section 5.4.5

F_s = Tabulated rolling shear stress (psi)
PDS, Table 3

F_s' = Allowable rolling shear stress including adjustments (psi)
Appendix, Section A2.4

F_v = Tabulated horizontal shear stress for lumber (psi)
NDS

f_r = Calculated raial stress (psi)
Part 1, Section 3.1.3

f_s = Calculated sheer stress (psi)
Part 1, Section 3.3.1.7.1

$f_{t,c}$ = Calculated stress in extreme fiber (psi) in tension or compression
Part 1, Section 3.3.1.6

f_v = Calculated shear stress (psi)
Part 1, Section 3.3.1.7.1

G_c = Tabulated modulus of rigidity of core in compression (psi)
Part 1, Section 3.1.2.2 and core manufacturer

H = Calculated horizontal reaction (lb per foot)
Figure 3.3.1.1 and Appendix, Section A1.4

h = Total depth of panel (inches)
Part 1, Sections 3.1.3 and 3.3.1.7.2

I = Calculated moment of inertial (in.^{4} per ft width, or per rib section)
Part 1, Sections 3.3.1.7.1 and 3.3.1.9

ℓ = Horizontal span length (inches)
Part 1, Section 3.2.1

M = Calculated bending moment (in.-lb)
Part 1, Sections 3.1.3, 3.3.1.6 and 3.3.1.9

m = Calculated moment due to unit load (in.-lb)
Part 1, Section 3.3.1.9

P = Direct force (lb per foot of width of arch)
Part 1, Section 3.3.1.6

P_L = Calculated force tangent to panel (lb per foot of width)
Appendix, Section A1.5

P_R = Calculated force tangent to panel (lb per foot of width)
Appendix, Section A1.5

p = Desired pressure on core (psi)
Part 2, Sections 3.2.3 and 3.3.2

q = Calculated shear stress in core (psi)
Part 1, Section 3.3.1.7.2

R = Radius of curvature (inches)
Part 1, Sections 2.2.1.1 and 3.1.3

R_v = Calculated vertical end reaction (lb per foot of width)
Appendix, Section A1.3

S = Section modulus (in.^{3} per ft of width)
Part 1, Section 3.3.1.6

s = Length between unit loads along arch (inches)
Part 1, Section 3.3.1.9

t = Distance beteen extreme fibers of plies parallel with the stress for one lamination (inches)
Part 1, Section 2.2.1

t_c = Thickness of core (inches)
Part 1, Section 3.3.1.7.2

V = Shear acting normal to slope (lb per ft of arch width, or per rib section)
Part 1, Section 3.3.1.7.1

V_L = Calculated force normal to panel (lb per foot of width)
Appendix, Section A1.5

V_R = Calculated force normal to panel (lb per foot of width)
Appendix, Section A1.5

V_1 = Allowable shear carried by wood framing members (lb per full panel width)
Part 1, Section 3.3.1.7.2 and NDS

V_2 = $V\text{-}V_1$ (lb per full panel width)
Part 1, Section 3.2.1

y = rise at mid-span (inches)
Part 1, Section 3.2.1

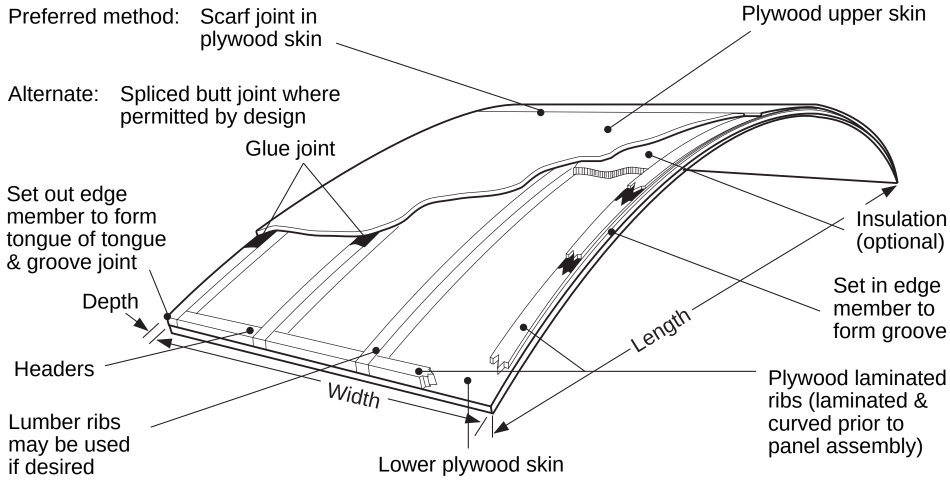
Δ = Difference between framing thickness and core thickness (inches)
Part 2, Section 3.2.3

Δ_a = Calculated deflection at point “a” (inches)
Part 1, Section 3.3.1.9

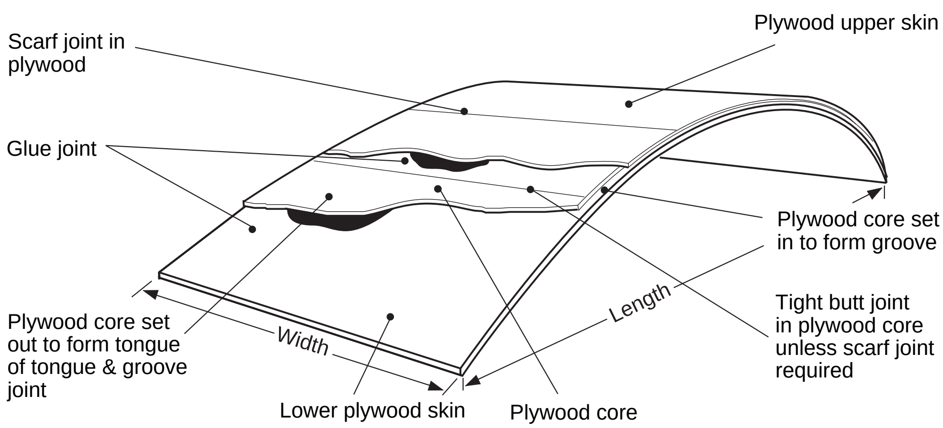
Δ_H = Horizontal deflection at support (inches)
Part 1, Section 3.2.1

Δ_v = Vertical deflection at mid-span (inches)
Part 1, Section 3.2.1

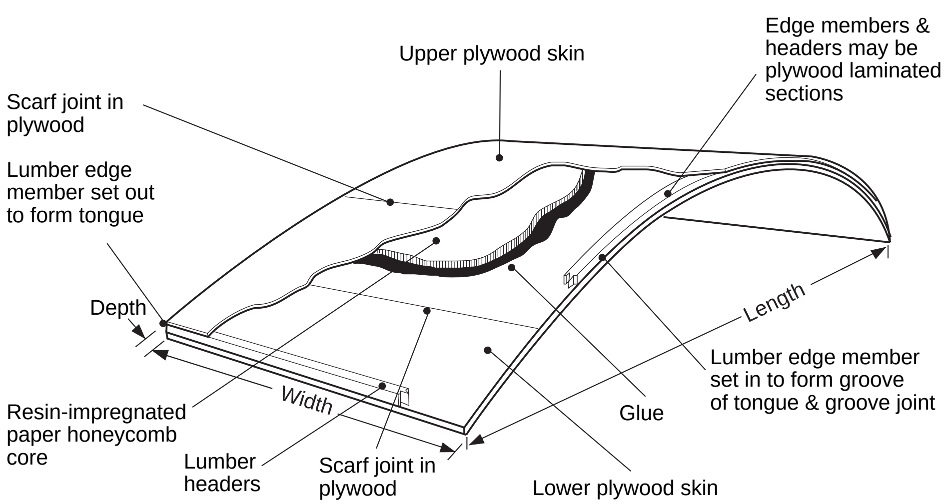
Typical Panel Using Curved Plywood Ribs



Typical Panel Using Solid Plywood Core



Typical Panel Using Lightweight Sandwich Core



PART 1 — Design of Plywood Curved Panels

1. Types of Curved Panels

1.1 Structural Types

Curved panels may be designed as either of two structural types, depending on whether horizontal deflection is restrained.

1.1.1 Curved Flexural Panels

A curved flexural panel is an arch panel without horizontal restraints such as tie rods or abutments. This type performs in flexure in the same way as a conventional flat panel, acting as a simple beam. To avoid damage to the supporting structure, bearing details must be designed accordingly, with provision for horizontal deflection, since no horizontal restraints are used.

Thickness is generally greater than for arch panels of the same span. Construction is usually with spaced ribs, to achieve the necessary thickness. Stresses are only slightly affected by radius of curvature.

1.1.2 Arch Panels

Arch panels are stressed both in compression and in flexure. Since their design does not permit horizontal deflection, they exert horizontal thrust at the supports, and therefore require tie rods or abutments. These panels are relatively thin, and stresses are considerably affected by radius of curvature.

Arches are generally of constant cross section, and continuous from support to support, without rotational fixity at the supports. In this case they are called "two-hinged," and are statically indeterminate.

For longer spans, two arch segments may be joined together to form a "three-hinged" arch. The joint, or hinge, is not moment-resisting, and the resulting member is statically determinate.

1.2 Shape

1.2.1 General

Curved panels may be made in any desired shape within the limits of fabrication of the materials used. Compound curvature (simultaneous curvature in two directions as for a dome shape) is normally not possible with plywood. For convenience in design and fabrication, circular curves are generally specified.

1.2.2 Limits of Curvature

Panels of medium curvature (between perhaps 3-1 and 8-1 span-rise ratios) are most practical. With panels of low rise, outward thrusts become very high and small outward movements at the supports can cause undesirable deflections of the panel. Panels with very high rise must be especially designed for resistance to lateral forces such as wind, since they become less stable as they approach semi-circular shape.

1.2.3 Bending Radii

See PLYWOOD DESIGN SPECIFICATION (PDS), Table A2, for minimum bending radii of plywood skins.

1.3 Core Types

Plywood curved panels consist of full-length plywood skins top and bottom, spaced by and joined with glue to a structural core capable of resisting the shearing forces.

1.3.1 Spaced Ribs

For all spans the core may consist of a single piece of laminated plywood or lumber ribs spaced as required, either pre-glued or glued during panel assembly. Such construction can readily include blanket insulation. The ribs usually parallel the span, where they contribute to the moment of inertia of the panel, and serve to resist shear. For some short spans, however, the ribs may be oriented parallel to the axis of the arch, where they serve primarily as spacers for the plywood skins.

1.3.2 Plywood Core

For short spans the core may consist of one or more layers of plywood, butt-jointed or full length, usually glued over the full area to the skins. In some cases glue need be applied only in strips, making the attachment similar to that in spaced-rib panels. Such "strip-gluing," where applicable, offers reduced fabrication costs.

1.3.3 Sandwich Core

Sandwich material, such as resin-impregnated paper honeycomb or foamed plastic, may be used for the core where light weight is desired.

2. Design Considerations

2.1 Design Loads

2.1.1 Uniform Load

The design live loads must not be less than required by the governing building regulations. Dead load is the actual weight of the panel and any permanent elements it supports, such as the roof membrane.

Curved panels must support dead load over the full area of the panel, plus live load over any portion of the panel. Loads may be assumed distributed over the horizontal projection of the panel.

For curved flexural panels the critical loading condition will be with dead load and live load distributed over the full panel area. For arch panels, both this condition, and that of live load over only one-half of the span, should be considered.

2.1.2 Concentrated Erection Load

Curved panels should be adequate to support, at any point of the span, a concentrated load such as that of several workmen standing, or roofing materials piled in one area. This load might come before or after adjoining panels are fastened together.

Curved panels should be designed for a minimum concentrated erection load of 150 lb per ft of panel width, with a 25% increase in allowable stresses permitted for the short duration of the load.

2.1.3 Wind Load

Panels, including anchorage details, must be designed to resist suction due to wind load, combined with internal pressure developed by wind through openings in the side walls, minus the dead load of the panels and roofing. Such loading may equal or exceed the gravity load, thereby causing stress reversal in the panels and tie rods.

2.2 Allowable Working Stresses

2.2.1 Plywood Faces

Stresses for design of plywood faces depend on the radius, the type of core, and the joints in the plywood.

2.2.1.1 Curvature Factor — For the curved portion of members the allowable unit stress in bending and in tension and compression parallel with the grain shall be modified through multiplication by the following curvature factor:

$$1 - 2000 \left(\frac{t}{R}\right)^2$$

in which

t = distance between extreme fibers of plies parallel with the stress for one lamination (inches). Normally it is the thickness of one face panel.

R = radius of curvature at mid-depth of the curved panel (inches)

The ratio t/R shall not exceed 1/100 for hardwoods and for southern pine, nor 1/125 for softwoods other than southern pine.

2.2.1.2 With Spaced Ribs — Allowable stresses in compression and tension given in PLYWOOD DESIGN SPECIFICATION, and reduced for curvature as above may require further reduction. As described in PDS Supplement 3, DESIGN AND FABRICATION OF PLYWOOD STRESSED-SKIN PANELS Part I, Sec. 3.2.2 and 3.5.4, the ratio of actual rib spacing to design basic spacing for a given skin thickness will determine the need and extent of the reduction.

2.2.1.3 With Honeycomb, Foam, or Plywood Core — Working stresses for plywood in flexure, compression, and tension are given in the PDS, and must be reduced for curvature as above.

2.2.2 Core Materials

The working stress in shear for paper honeycomb or foamed plastic core should not exceed one-third of its ultimate shear strength in the appropriate direction for the moisture condition and type of end joint used.

2.3 Effective Sections

All plywood and all lumber having its grain parallel to the direction of stress may be considered effective in resisting the stress, subject to the following restrictions.

2.3.1 For Bending and Compression

2.3.1.1 Spaced-Rib Panels — See DESIGN AND FABRICATION OF PLYWOOD STRESSED-SKIN PANELS for reductions due to splice plates and transverse deformation.

2.3.1.2 Plywood Core and Laminated Ribs — The effective strength of solid-plywood-core panels and of laminated ribs in a spaced-rib panel at a section containing a butt joint in any lamination may be determined by ignoring the butted lamination, and any other lamination containing a butt joint closer than 50 times the lamination thickness. When the butt joint occurs in the tension portion of the cross section, the allowable fiber stress in bending for the remaining parallel-grain material must be multiplied by 0.8.

2.3.1.3 Honeycomb or Foamed Plastic Core — Paper honeycomb or foamed plastic core should not be assumed to resist any flexural or direct compression stresses.

2.3.2 For Shear and Deflection

Shear and deflection of a curved panel containing butt joints in either the core or the faces may be based on the cross section of all material having its grain parallel with the direction of principal stress.

2.4 Allowable Deflection

The maximum deflection for roofs should not exceed 1/240th of the span under live load, nor 1/180th of the span under dead-plus-live load. There need not be a limit for deflection under the concentrated erection load.

3. Design Method

3.1 Considerations Common to Both Curved Flexural Panels and Arch Panels

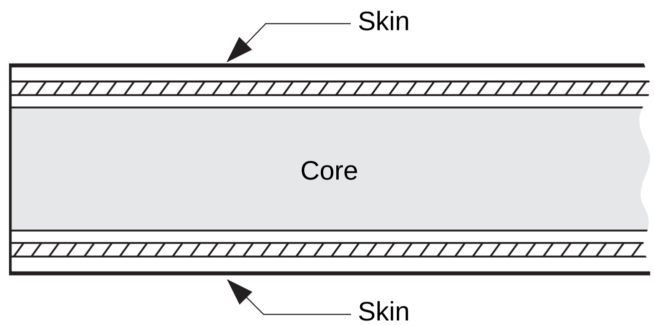
To prevent damage to the supporting structure, curved flexural panels must be designed so that no thrust can be developed. For arch panels, direct compression stress must be added to bending stress.

3.1.1 Spaced-Rib Panels

Design of curved spaced-rib panels is similar to that of flat stressed-skin panels as given in DESIGN AND FABRICATION OF PLYWOOD STRESSED-SKIN PANELS. The information in that design method is basic to all panel design.

3.1.2 Sandwich Panels

Design of curved sandwich panels is similar to that for flat sandwich panels as given in PDS Supplement 4, DESIGN AND FABRICATION OF PLYWOOD SANDWICH PANELS. It is based on the assumption that parallel-grain material in the skins carries all bending forces, while the core carries only shear.



3.1.2.1 Basic Properties — Compute neutral axis, moment of inertia, and section modulus based on area of the skins. Figure two values of section modulus, one for top, one for bottom, if neutral axis is not at centerline of panel depth.

3.1.2.2 Critical Stress — Determine approximate skin buckling stress. Maximum combined stress, when computed, must be less than F_c, and less than one-third of the value of C_{cr}.

$$C_{cr} = 0.5 \sqrt[3]{EE_cG_c}$$

where

C_{cr} = critical skin buckling stress (psi)

E = modulus of elasticity of plywood (psi)

E_c = modulus of elasticity of core in compression (psi)

G_c = modulus of rigidity of core in compression (psi).

This critical stress represents the value at which the skin may be expected to suffer local buckling, crushing the core or causing the core to fail in tension normal to the skins.

3.1.3 Radial Stresses

When a curved member is subjected to bending moment, a radial stress is induced. When the moment is in the direction tending to decrease curvature (increase the radius) the stress is in tension. When the moment is in the direction tending to increase curvature (decrease the radius) the stress is in compression.

This radial tension or compression stress is given by the following equation. It must be less than the allowable values given in the PDS for plywood and in NDS for lumber. For sandwich panel core material it should be less than one-third of the allowable shear value of the core.

$$f_r = \frac{3}{2}\,\frac{M}{Rbh}$$

where

f_r = radial stress (psi) due to moment, M

M = bending moment (in.-lb) on a width of panel equal to the rib spacing for spaced-rib panels,or a 1-ft width for sandwich panels

R = radius of curvature at centerline of element being analyzed (in.)

b = width of rib (in.) for spaced-rib panels, or 12″ or sandwich panels

h = over-all depth of panel (in.).

3.1.4 Curvature Factor

Allowable stresses must be reduced for curvature, as in Section 2.2.1.

3.2 Curved Flexural Panels

3.2.1 Horizontal Deflection at Supports

The horizontal deflection at the free support of a curved panel that is free to deflect horizontally at one end may be determined from the following equation:

$$\Delta_H = \frac{y\Delta_v}{\ell}$$

where

Δ_H = horizontal deflection at support (in.)

y = rise of curved panel at mid-span (in.)

Δ_v = vertical deflection of curved panel at mid-span due to vertical load (in.)

ℓ = horizontal span length (in.).

This equation, while approximate, is sufficiently accurate to determine the amount of space to allow at supports for the horizontal deflection to take place, so as to avoid developing thrust that is not provided for in the design.

3.2.2 Connections

3.2.2.1 Connections to Supports — Connections of panels to supporting members must provide for the horizontal movement calculated under Section 3.2.1 above. Lag screws or bolts in slotted or oversize holes in the panels are generally suitable. Connections must be adequate to resist the uplift as found in Section 2.1.3, as well as any shear that may be developed by diaphragm action.

3.2.2.2 Connections between Panels — Connections between panels must be adequate to make them perform as a unit; to transfer concentrated erection loads between panels without excessive differential deflection; and to transfer any other shear developed by diaphragm action. Tongue-and-grooved joints or nailed plywood battens are generally suitable.

3.3 Arch Panels

(See Appendix for Outline Design Example.)

3.3.1 Design

Two-hinged arch panels may be designed using the procedure outlined below. The solution for three-hinged arches is the same as that outlined for two-hinged arches, except that the horizontal thrust is calculated by statics instead of by use of the graph, Figure 3.3.1.1.

3.3.1.1 Reactions — Calculate the vertical reactions and horizontal thrusts of the arch for the various conditions of loading. (See Section 2.1.) Figure 3.3.1.1 will simplify this step.

Since the Thrust Coefficient graph is set up for loads at the tenth points of the span, it is necessary to break up the uniform load into equivalent concentrated loads acting at these points. Ignore the load on 0.05 of the span adjacent to each support (it has negligible influence on the thrust) and divide the remainder into equal sections with concentrated loads at their midpoints. The graph then gives thrust coefficients, which, when multiplied by the load, yield the thrust produced by that load.

3.3.1.2 Moments — Calculate by statics and plot the moments at convenient intervals along the arch for the various conditions of loading. A convenient interval, if the Thrust Graph is used, is obtained by dividing the span into ten equal parts.

3.3.1.3 Maximum Moments — By inspection of the moment curves, determine the most severe loading condition and the magnitude of maximum moment. Worst case for maximum moment will usually occur either with dead load plus concentrated erection load, or with dead load plus half-span live load. In either case it will be near the quarter point of the span.

3.3.1.4 Direct Stress — Calculate the direct stress at the point of maximum moment by resolving acting forces into components tangential to the slope of the arch.

3.3.1.5 Trial Section — Guided by the moment and direct stress figured above, assume a trial cross section for the arch and calculate its weight and section properties.

3.3.1.6 Combined Stresses — Calculate the maximum combined stresses in the plywood at the point of maximum moment.

The combined stresses due to bending and compression must not exceed values given in Section 2.2; they may be calculated by the formula:

$$f_{t,c} = \frac{P}{A_{||}} \pm \frac{M}{S}$$

where

$f_{t,c}$ = stress in extreme fiber (psi) tension or compression

P = direct force (lb per ft width of arch)

$A_{||}$ = area of material with grain parallel to stress

M = bending moment (in.-lb)

S = section modulus (in.^{3} per ft width of arch).

3.3.1.7 Shear — Determine the maximum shear normal to the slope of the arch. Maximum shear occurs at the ends for both dead load and full-span uniform live load. Maximum shear for half-span load occurs at the center of the span, with shears at the ends almost as high for most span-to-rise ratios. (This shear equals one-quarter of the unbalanced load.) Maximum shear due to concentrated erection load will probably occur at an end, when the load is placed near that end.

3.3.1.7.1 Spaced-Rib and Plywood-Core Panels — For plywood, the shear stress must not exceed rolling shear values given in the PLYWOOD DESIGN SPECIFICATION. For solid-wood-rib-core panels, the shear stress must not exceed the design horizontal shear for the wood species used as ribs. Shear stress may be calculated by the formula:

$$f_s = \frac{VQ}{Ib}$$

where

f_s = shear stress (psi) either rolling shear in plywood, or horizontal shear in solid rib

V = shear acting normal to the slope of the arch (lb per ft of arch width, or per rib section)

Q = first moment about neutral axis of area of parallel-grain material from panel face inward to plane at which shear stress is to be calculated (in.^{3} per ft width of arch panel, or per rib section)

I = moment of inertia of arch panel (in.^{4} per ft width of arch panel, or per rib section)

b = width of rib (in.) for spaced-rib panel; width of glued strip for strip-glued solid-core panel; or 12″ for solid-plywood-core panel glued over its total area.

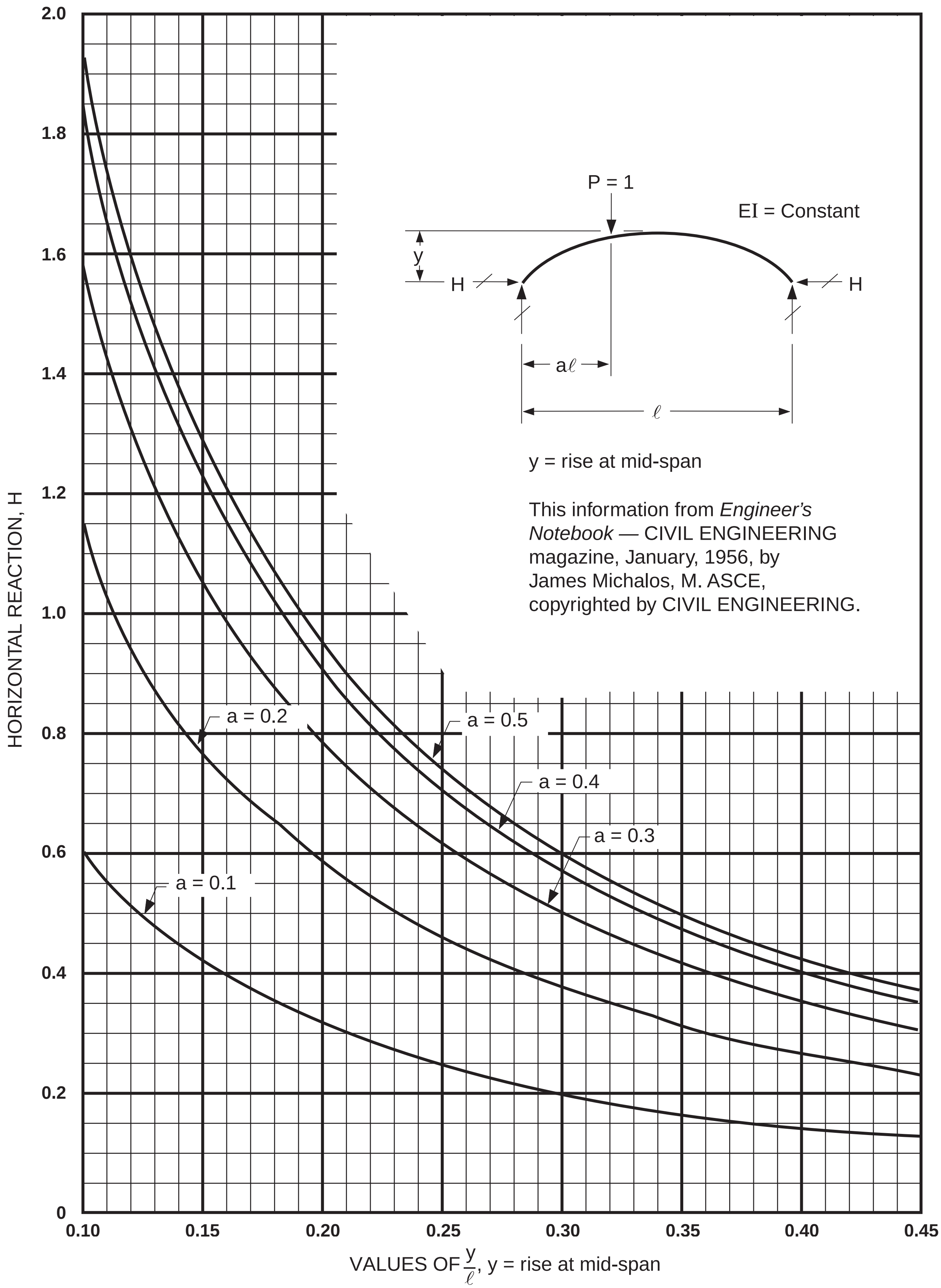


FIGURE 3.3.1.1 Thrust Coefficients for 2-Hinged Circular Arches

3.3.1.7.2 Honeycomb or Foamed-Plastic Core — Shear stress in the core shall not exceed guidelines given in Section 2.2.2; stress may be computed by the following formula (which allows credit for that portion of the shear resisted by wood edge members):

$$q = \frac{2V_2}{(h + t_c)b_c}$$

where

- q = shear stress in core (psi)
- V_2 = $V - V_1$ = total shear acting normal to the slope of the arch minus allowable shear carried by wood framing members (lb per full panel width)
- h = total depth of panel (in.)
- t_c = thickness of core (in.)
- b_c = width of core per full panel (in.).

3.3.1.8 Radial Stresses — Calculate radial stresses as in Section 3.1.3.

3.3.1.9 Deflection — Calculate the maximum deflection of the arch for the various conditions of loading.

Deflection of arch panels must not exceed values given in Section 2.4, and may be determined by solving the following equation, which ignores the minor portions of deflection due to shear and direct stress:

$$\Delta_a = \frac{s}{EI} \Sigma Mm$$

where:

- Δ_a = deflection at point "a" in same direction as unit load, or center of "uniform" load approximated with unit loads (in.)
- M = moment due to the load or loads which cause the deflection (in.-lb per ft of panel width)
- m = moment due to unit load at point "a" (unit load-in.)
- s = length (in.) between unit loads along arch. (Ten equal-length segments are usually sufficient, though any number may be used.)
- E = modulus of elasticity (psi) of plywood faces in arch (1,800,000 for Group 1)
- I = moment of inertia of arch panel (in.^{4} per ft of panel width).

3.3.1.10 Final Section — Revise the trial cross section if necessary and repeat appropriate calculations.

3.3.2 Connections and Supports

3.3.2.1 Connections to Supports — Connections of panels to supporting members may be with nails, lag screws, bolts, or other means adequate to resist the maximum horizontal thrust and uplift, as well as any shear developed by diaphragm action.

3.3.2.2 Connections Between Panels — Connections between adjacent curved panels must be adequate to make them perform as a unit, to transfer concentrated erection loads between adjacent panels without excessive differential deflection, and to transfer any shear developed by diaphragm action. Tongue-and-grooved joints, or nailed plywood battens are generally suitable.

3.3.2.3 Supports — Horizontal supporting members for panels must be adequate to resist vertical and horizontal loads between their own supports without excessive deflection. Horizontal thrust must be resisted by properly designed tie rods, struts, or abutments.

3.3.2.4 Tie Rods — Where tie rods are used to resist thrust, such rods or other effective means of resisting thrust must be placed in all bays.

3.3.2.5 Abutments — Where abutments are used at the outer edges of exterior bays, means of resisting thrust must be placed in all bays. Such means of resisting thrust may include struts, shear walls, or other devices.

Spacing should be as required by the interior panel supporting members. Such struts are required to provide for unbalanced loads when not all bays are equally loaded.

3.3.2.6 Diaphragms — Where diaphragm action is assumed, struts and chords must be provided as required by diaphragm forces.

PART 2—Fabrication of Plywood Curved Panels

1. General

1.1

This specification covers the fabrication of glued plywood curved panels with cores of spaced plywood or lumber ribs, solid plywood, or low-density material. Low-density core material may be preformed paper honeycomb, foamed plastic, or other material of demonstrated strength and durability for which accepted shear strength, shear modulus, compressive strength and compressive modulus values are available. Such core material may be used with or without auxiliary wood members.

1.2

Plywood curved panels should be designed by a qualified architect or engineer in accordance with the latest edition of the APA PLYWOOD DESIGN SPECIFICATION (PDS), using the method set forth in Part 1 of this PDS Supplement. Other design methods may be employed, provided they are supported by adequate test data.

1.3

Plywood curved panels shall be fabricated and assembled in accordance with engineering drawings and specifications, except that minimum requirements herein shall be observed.

1.4

The plywood use recommendations contained in this publication are based on APA's continuing program of laboratory testing, product research and comprehensive field experience. However, there are wide variations in quality of workmanship and in the conditions under which plywood is used. Because the Association has no control over those elements, it cannot accept responsibility for plywood performance or designs as actually constructed.

2. Materials

2.1 Plywood

2.1.1

Plywood shall conform with the latest edition of U.S. Product Standard PS 1 for Construction and Industrial Plywood. Each original panel shall bear the trademark of APA. Any precut plywood shall be accompanied by an affidavit from the precutter certifying that each original panel was of the specified type and grade, and carried the trademark of APA.

2.1.2

At the time of gluing, the plywood shall be conditioned to a moisture content between 7% and 16%. Pieces to be assembled into a single curved panel shall be selected for moisture content to conform with Section 3.3.1.

2.1.3

Surfaces of plywood to be glued shall be clean and free from oil, dust, paper tape, and other material which would be detrimental to satisfactory gluing. Medium density overlaid surfaces shall not be relied on for a structural glue bond.

2.2 Lumber

2.2.1

Grades shall be in accordance with current lumber grading rules, except that knotholes up to the same size as the sound and tight knots specified for the grade by the grading rules may be permitted. When lumber is resawn, it shall be regraded on the basis of the new size.

2.2.2

At the time of gluing, the lumber shall be conditioned to a moisture content between 7% and 16%. Pieces to be assembled into a single sandwich panel shall be selected for moisture content to conform with Section 3.3.1.

2.2.3

Surfaces of lumber to be glued shall be clean and free from oil, dust and other foreign matter which would be detrimental to satisfactory gluing. Each piece of lumber shall be machine finished, but not sanded, to a smooth surface with a maximum allowable variation of 1/32″ in the surface to be glued. Warp, twist, cup or other characteristics which would prevent intimate contact of mating glued surfaces shall not be permitted.

2.3 Glue

2.3.1

Glue shall be of the type specified by designer for anticipated exposure conditions and must be compatible with the core material being used.

2.3.2

Interior-type glue shall conform with ASTM Specification D3024 or D4689. Exterior-type glue shall conform with ASTM Specification D2559.

2.3.3

Mixing, spreading, storage-, pot-, and working-life, and assembly time and temperature shall be in accordance with the manufacturers' recommendations for the specific core and facing materials used.

2.4 Core Material

2.4.1

Properties of foamed plastic and other materials shall be in accordance with the design, and compatible with the glue being used.

2.4.2

Paper honeycomb shall be pre-expanded, resin-impregnated kraft of specified paper weight, resin content and cell size.

3. Fabrication

3.1 Skins

3.1.1

Slope of scarf joints in plywood skins shall not be steeper than 1 in 8. Scarf joints shall be glued under pressure over their full contact area, and shall meet the requirements of PS 1, Section 3.9. In addition, the aggregate width of all knots and knotholes falling wholly within the critical section shall be not more than 10 inches on each face of the jointed panel for a 4-ft-wide panel, and proportionately for other widths. The critical section for a scarf joint shall be defined as a 12-inch-wide strip, 6 inches on each side of the joint in the panel face, extending across the width of the panel.

3.1.2

Butt joints in plywood skins shall be backed with plywood splice plates centered over the joint and glued over their full contact area. Splice plates shall be at least equal in thickness to the skin, except that minimum thickness shall be 1/2″ if nail-glued. Minimum splice plate lengths, face grain parallel with that of the skin and centered over the joint, shall be as follows (unless otherwise called for in the design):

Skin Thickness	Splice Plate Length
1/4″	6″
5/16″	8″
3/8″ sanded	10″
3/8″ unsanded	12″
1/2″	14″
5/8″ – 3/4″	16″

3.1.3

Surfaces of high density overlaid plywood to be glued shall be roughened, as by a light sanding, before gluing.

3.2 Framing

3.2.1

Scarf and finger joints may be used in auxiliary framing members, provided the joints are as required for the grade and stress used in the design. Knots or knotholes in the end joints shall be limited to those permitted by the lumber grade, but in any case shall not exceed 1/4 the nominal width of the piece. When the design permits butt joints in laminated ribs, they shall be staggered at least 30 times the lamination thickness.

3.2.2

The edges of the framing members to which the plywood skins are to be glued shall be surfaced prior to assembly to limit variation in depth to 1/16″ for all members in a panel.

3.2.3

In order to provide gluing pressure for the core material and auxiliary framing members simultaneously, wood framing members shall be surfaced so that they are ``shallower" than the core. The difference in depth shall be given by the following equation:

$$\Delta = \frac{t_c p}{E_c}$$

where

- Δ = amount that framing is "shallower" than core (in.)
- t_c = total depth of core (in.)
- p = desired pressure on core (see Part 2, Section 3.3.2) (psi)
- E_c = modulus of elasticity of core in compression (psi).

3.3 Assembly

3.3.1

The difference in moisture contents of the various pieces assembled into a single curved panel shall not exceed 5%.

3.3.2

Plywood skins shall be glued to auxiliary framing members and core material over their full contact area, using a means that will provide close contact and substantially uniform pressure. Where clamping or other positive mechanical means are used, the pressure on the net framing area shall be sufficient to provide adequate contact and ensure good glue bond, and shall be uniformly distributed by caul plates, beams, or other effective means. 100 to 150 psi on the net glued area is recommended for wood-to-wood joints. For sandwich panels, a pressure equal to from 40% to 60% of the compressive yield strength of the core is suggested.

In place of mechanical pressure methods, nail-gluing may be used for ribbed panels or panels having solid plywood cores. Nail sizes and spacings shown in the following schedule are suggested as a guide:

> Nails shall be at least 4d for plywood up to 3/8″ thick, and 6d for 15/32″ to 7/8″ plywood. They shall be spaced not to exceed 3″ along the framing members for plywood through 3/8″, or 4″ for plywood 15/32″ and thicker, using one line for ribs 2″ wide or less, and two lines for ribs more than 2″ and up to 4″ wide. Panels having solid plywood cores may be glued using staples or nails spaced not to exceed 6″ both ways.

Application of pressure may start at any point, but shall progress to an end or ends. In any case, **it shall be the responsibility of the fabricator to produce a continuous glue bond which meets or exceeds applicable specifications.**

3.3.3

Where a tongue-and-groove type panel edge joint is specified (and not otherwise detailed), the longitudinal framing member forming the tongue shall be of at least 2″ nominal width, set out 3/4″ ± 1/16″ from the plywood edge. Edges of the tongue may be eased to facilitate ease of assembly, but still must provide a flat area at least 3/8″ wide (See diagram, Sec. A2.3). Any corresponding framing member forming the base of the groove shall be set back 1/4″ to 1″ more than the amount by which the tongue protrudes. One skin may be cut back slightly to provide a tight fit to the adjacent panel for the opposite skin.

3.3.4

Unless otherwise specified, panel chord length, width and thickness shall be accurate within ± 1/8″. Panel edges shall be straight within 1/16″ for an 8-ft length and proportionately for other lengths. Panels in the same group shall not vary in thickness by more than 1/16″, in arc length by more than 1/4″, nor from design rise by more than 5%.

Panels shall be square, as measured on the chord diagonals, within 1/8″ for a 4-ft-wide panel and proportionately for other widths. Panels shall lie flat at all bearing points within 1/4″ for 4-ft x 8-ft panels, and proportionately for other sizes. Panel edge cross sections shall be square within 1/16″ for constructions with lumber stringers 4″ deep, and proportionately for other sizes.

3.3.5

In ribbed panels, insulation, vapor-barrier materials and ventilation shall be provided as specified in the design.

Such materials shall be securely fastened in the assembly in such a way that they cannot interfere in the process of gluing the plywood skins, or with the ventilation pattern. When ventilation is specified, panels shall be vented through blocking and headers on the cool side of the insulation. Provision shall be made to line up the vent holes within and between panels. Ribs shall not be notched for ventilation, unless so specified.

4. Test Samples

4.1

When glue-bond test samples are taken from a member, if not otherwise obtained from trim, they shall be taken as cores approximately 2″ in diameter, drilled perpendicular to the plane of the skins, and no deeper than 3/4″ into any framing member. Cores may be cut either partially or entirely through the panel if they do not occur at framing.

4.2

No samples shall be taken from the same skin at width-wise cross sections closer together than 12″ along the length of the arc, except as detailed in paragraph 4.2.2 below. No more than 4 cores shall be taken from a 4-ft-wide panel, with a proportionate number from other widths. Samples shall be taken at a distance from the panel ends not greater than the panel depth, except as follows:

4.2.1

One sample may be taken from one of the outside longitudinal framing members, within the outer quarters of the panel length, provided the framing member is notched no deeper than 1/2″ below its edge. The other outside longitudinal framing member may be sampled similarly, but at the opposite end of the panel.

4.2.2

No more than two samples per butt joint at any one cross section may be taken from skin-splice plates. They shall be located midway between longitudinal framing members, and shall be aligned longitudinally, one on each side of the butt joint.

4.3

Where glue-bond test samples have been taken, holes shall be neatly plugged with glued wood inserts.

5. Identification

Each member shall be identified by the appropriate trademark of an independent inspection and testing agency, legibly applied so as to be clearly visible. Locate trademark approximately 2 feet from either end, except appearance of installed panel shall be considered.

Appendix — Outline Design Example for Arch Panel

Problem: Design curved arch-type panel with 8-ft span, 6-ft radius of curvature, for live load – 32 psf.

Assume dead load – 8 psf; Assume conc. erection load – 150 lb per foot of width. (Apply at 1/5 point.)

A1. Determine External and Internal Forces

A1.1 Distances

Break arch into ten segments and compute vertical and horizontal distances to each.

Point	**x**	**y**
0.0	0.0	0.0
.1	0.8′	0.60′
.2	1.6′	1.03′
.3	2.4′	1.31′
.4	3.2′	1.47′
.5	4.0′	1.53′
.6	4.8′	1.47′
.7	5.6′	1.31′
.8	6.4′	1.03′
.9	7.2′	0.60′
1.0	8.0′	0.0

A1.2 Thrusts

From Figure 3.3.1.1, page 7 (y = 1.53′), determine thrust coefficient for each increment, and for total uniform load. (H for half-span uniform load is just one-half H for total uniform load.) Maximum thrust will occur with full live load plus dead load on the total span.

Load at point	**Thrust coefficient**	**Thrust, H = thrust coefficient x w w = 0.8 ft x 40 psf**
0.0	0.0	0.0
.1	0.32	10.2
.2	0.60	19.2
.3	0.81	25.9
.4	0.95	30.4
.5	0.99	31.7
.6	0.95	30.4
.7	0.81	25.9
.8	0.60	19.2
.9	0.32	10.2
1.0	0.0	0.0
All points	6.35	203.2

ΣH (for full live load plus dead load) – 203 lb per ft of width.

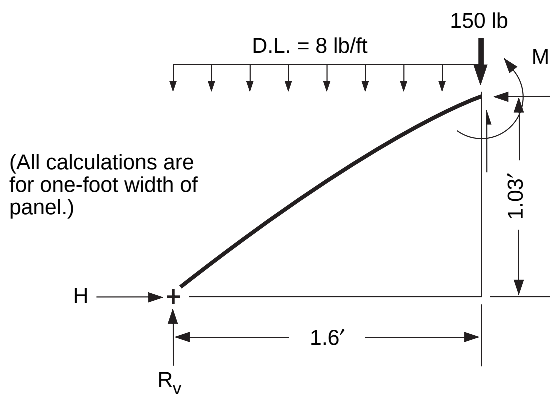
A1.3 Vertical Reaction

Compute maximum vertical reaction. It will be due to full live load plus dead load on the total span.

$$R_v = (32 + 8) \times \frac{8}{2} = 160 \text{ lb per foot of width}$$

A1.4 Maximum Moment

By simple statics find maximum moment at each point. Worst case for maximum moment will usually occur either with dead load plus concentrated erection load, or with dead load plus half-span live load. In either case it will occur near the quarter point of the span. In this example, dead load plus concentrated load causes by far the highest moment.



$$Rv = \frac{8 - 1.6}{8} \times 150 + \frac{8 \times 8}{2}$$

$$= 152 \text{ lb per foot of width}$$

$$H = 0.60 \times 150 + \frac{8}{40} \times 203.2$$

$$= 130.6 \text{ lb per foot of width}$$

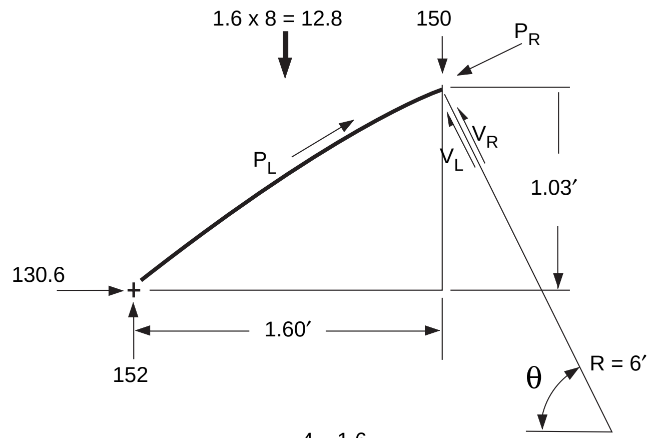
$$M = 152 \times 1.6 - 130.6 \times 1.03 - \frac{8 \times (1.6)^2}{2}$$

$$= 98.4 \text{ ft-lb per foot of width}$$

A1.5 Internal Forces

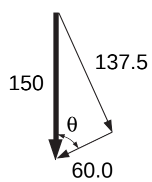
By statics, compute internal "forces" tangent and perpendicular to the slope of the arch at the point of maximum moment. This shear and "direct load" are those due to the applied load which causes the maximum moment – in this case the dead load plus the concentrated erection load.

Radial and tangential components of external forces:

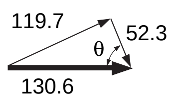


$$\cos\theta = \frac{4 - 1.6}{6}$$

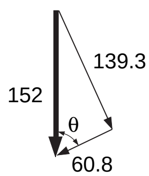
$$\theta = \frac{4 - 1.6}{6}$$



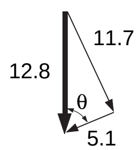
Concentrated Load



Thrust



Reaction



Dead Load

P_R = –60.0 + 119.7 + 60.8 – 5.1 = 115.4 lb per foot

P_L = 119.7 + 60.8 – 5.1 = 175.4 lb per foot

V_R = 137.5 + 52.3 – 139.3 + 11.7 = 62.2 lb per foot

V_L = 52.3 – 139.3 + 11.7 = –75.3 lb per foot

A1.6 Summary of Results

Max thrust (H), for full LL + DL over entire span (See Section A1.2) .... 203 lb/ft

Max vertical end reaction (R_v), from full load on entire span (See Section A1.3) .... 160 lb/ft

Max moment (M), for concentrated erection load at 0.2ℓ (See Section A1.4) .... 98 ft-lb/ft

Max shear at 0.2ℓ, for concentrated erection load at 0.2ℓ ($|V_L|$ above) .... 75 lb/ft

Tangential load at 0.2ℓ, for thrust, reaction and dead load (P_R above) .... 175 lb/ft

Moment, from DL + half-span LL* .... 34 ft-lb/ft

Shear at 0.5ℓ, for erection load at 0.5ℓ* .... 75 lb/ft

Shear at end, for erection load near end* .... 109 lb/ft

* Detailed calculations for these values are not shown. To determine values, analyze the curved panel using preceding calculations as a guide.

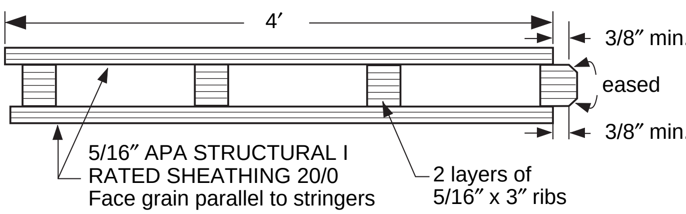
A2. Calculate Member Sizes to Resist Above Forces

A2.1 Stressed-Skin Panels

See DESIGN AND FABRICATION OF PLYWOOD STRESSED-SKIN PANELS for design of stressed-skin-type curved panels.

A2.2 Sandwich Panels

See DESIGN AND FABRICATION OF PLYWOOD SANDWICH PANELS, for design of sandwich-type curved panels. (For quick reference by those familiar with the basic principles of such designs, the method is summarized in Part 1, Section 3.1.2, page 4).



A2.3 Trial Section

Trial section, using DESIGN AND FABRICATION OF PLYWOOD STRESSED-SKIN PANELS

$A_{||}$ = 16.2 in.^{2} per 4-ft width

I = 3.14 in.^{4} per 4-ft width

Q_{NA} = 3.29 in.^{3} per 4-ft width

A2.4 Allowable Stresses

Using DESIGN AND FABRICATION OF PLYWOOD STRESSED-SKIN PANELS,

allowable flexural stress is

$$F_c' = 1540 \times 1.15 \times 0.67 \times 0.962 = 1141 \text{ psi}$$

- 1540 — Basic
- 1.15 — Load Duration Factor for Snow
- 0.67 — Rib Spacing Factor
- 0.962 — Curvature Factor

allowable horizontal shear stress is

PDS 3, Sec. 3.6.4

$$F_s' = \frac{(\frac{75}{2} \times 3) + (75 \times 3 \times 2) + (\frac{75}{2} \times 1.5) \times 1.15}{3 + 3 + 3 + 1.5}$$

$$= 67.8 \text{ psi}$$

allowable radial stress is

$$F_r' = \frac{67.8}{2} = 33.9 \text{ psi}$$

PDS, Sec. 5.4.5

A2.5 Final Stresses on Trial Section

Maximum combined stress,

$f_{max} = \frac{P}{A} \pm \frac{Mc}{I}$, is for worst case (concentrated erection load)

$$f_{max} = \frac{P}{A} + \frac{Mc}{I}$$

$$= \frac{4 \times 175}{16.2} + \frac{4 \times 98 \times 12 \times 5/8}{3.14}$$

$$= 43.2 + 936$$

$$= 979 \text{ psi} < 1141 \text{ psi}$$

$$f_s = \frac{VQ}{Ib} = \frac{109 \times 4 \times 3.29}{3.14 \times 12}$$

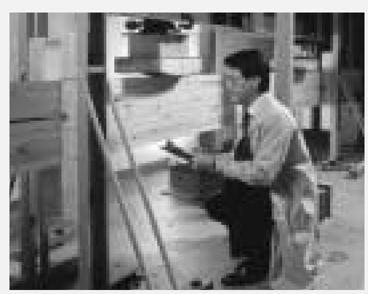
$$= 38.1 \text{ psi} < 67.8 \text{ psi}$$

$$f_r = \frac{3M}{2Rbh} = \frac{3 \times 98 \times 4 \times 12}{2 \times 72 \times 4 \times 3 \times 5/4}$$

$$= 6.5 \text{ psi} < 33.9 \text{ psi}$$

Tie rods required – could use 1/2″ diameter at 12′-0″

Trial Section O.K. as shown.



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A P A

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