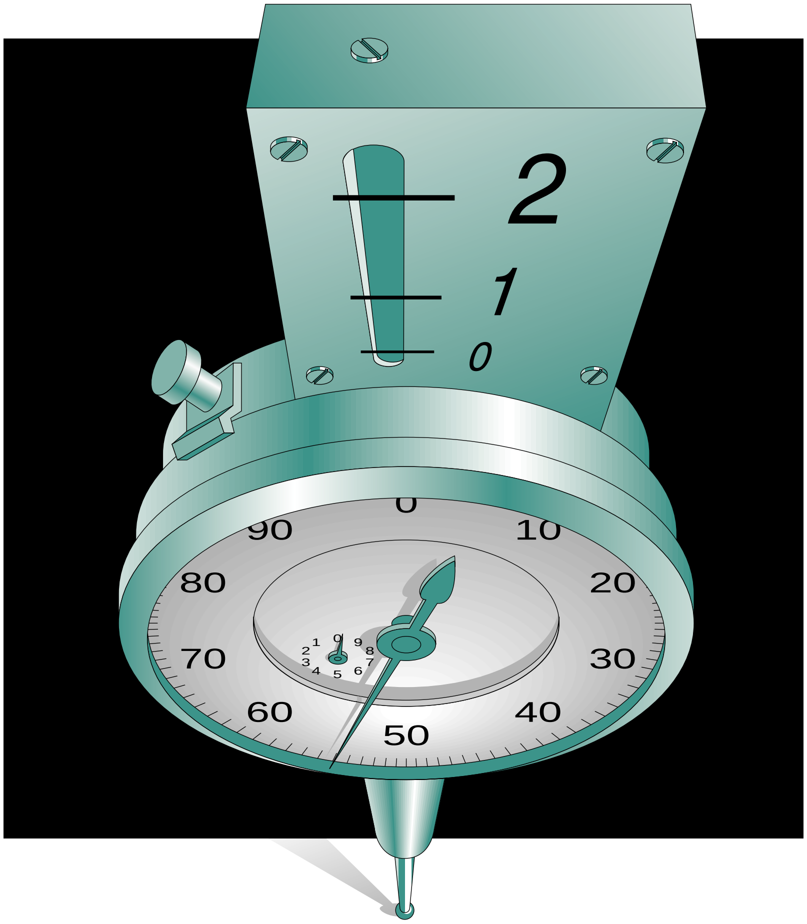
Report 138

PLYWOOD DIAPHRAGMS

by John R. Tissell, P.E. and James R. Elliott, P.E.
Technical Services Division



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Wood is the right choice for a host of construction applications. It is the earth's natural, energy efficient and renewable building material.

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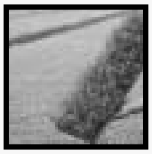
A few facts about wood.

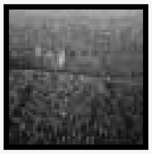
- ***We're not running out of trees.*** One-third of the United States land base – 731 million acres – is covered by forests. About two-thirds of that 731 million acres is suitable for repeated planting and harvesting of timber. But only about half of the land suitable for growing timber is open to logging. Most of that harvestable acreage also is open to other uses, such as camping, hiking, and hunting. Forests fully cover one-half of Canada's land mass. Of this forestland, nearly half is considered productive, or capable of producing timber on a sustained yield basis. Canada has the highest per capita accumulation of protected natural areas in the world – areas including national and provincial parks.



- ***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. Canada's replanting record shows a fourfold increase in the number of trees planted between 1975 and 1990.

- ***Manufacturing wood 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, the miracle material for the environment, for design, and for strong, lasting construction.

APA
THE ENGINEERED
WOOD ASSOCIATION
RATED SHEATHING
32/16 15/32 INCH
SIZED FOR SPACING
EXPOSURE 1
000
PS 1-95 C-D PRP-108

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

PLYWOOD DIAPHRAGMS

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Abstract

Commonly accepted plywood diaphragm construction is applicable for design shears significantly higher than those previously published. Multiple rows of fasteners in wide framing members are used to develop the higher shear loads sometimes required for buildings in Seismic Zone 4. This report details the design and testing of eleven diaphragms, up to the limiting shear stress of the plywood. The effects of openings in the diaphragm and field gluing of plywood sheathing are also investigated.

CONTENTS

Control Diaphragm – Panelized Construction

High-Load Diaphragm – Two-Layer Panelized Construction

High-Load Diaphragms – Conventional Construction

Diaphragms With Openings

Field-Glued Diaphragms

Diaphragm With Framing Spaced 5 Ft o.c

RECOMMENDED SHEARS FOR HIGH-LOAD WOOD STRUCTURAL PANEL DIAPHRAGMS

The table on the following page of allowable design shears for high-load wood structural panel diaphragms has been derived from test results given in the body of this report, with suitable reference to all previous tests of horizontal plywood diaphragms. (See Appendix A for a table of previously accepted design shears and a summary of previous diaphragm tests.) Tabulated shears are for wind or seismic loading. Reduce values 25% for "normal" load duration.

Note: Allowable high-load shear values in Table 1 were derived based on the principles in this report and European Yield Model (EYM) provisions for fastener lateral loads, per the 1997 Edition of the National Design Specification *(19)*.* See ICBO ES Evaluation Report No. 1952 *(20)*.

Allowable design shears assume that all framing, splices, ties, hold-downs and other connections are adequately designed and detailed for such loads.

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*Italicized numbers in parentheses refer to literature cited.

TABLE 1

ALLOWABLE SHEAR IN POUNDS PER FOOT FOR HIGH-LOAD HORIZONTAL BLOCKED DIAPHRAGMS WITH FRAMING OF DOUGLAS FIR, LARCH OR SOUTHERN PINE[1] FOR WIND OR SEISMIC LOADING[2]

	Fastener					Cases 1 and 2[4]					
						Fastener spacing per line at boundaries					
						4 inches		2-1/2 inches		2 inches	
						Fastener spacing per line at other panel edges					
Panel Grade[3]	Type	Minimum Penetration in Framing (inches)	Minimum Nominal Thickness (inch)	Minimum Nominal Width of Framing Member (inches)	Lines of Fasteners	6 inches	4 inches	4 inches	3 inches	3 inches	2 inches
Structural I	10d common nails	1-5/8	15/32	3	2	605	815	875	1,150	–	–
				4	2	700	915	1,005	1,290	–	–
				4	3	875	1,220	1,285	1,395	–	–
			19/32	3	2	670	880	965	1,255	–	–
				4	2	780	990	1,110	1,440	–	–
				4	3	965	1,320	1,405	1,790	–	–
			23/32	3	2	730	955	1,050	1,365	–	–
				4	2	855	1,070	1,210	1,565	–	–
				4	3	1,050	1,430	1,525	1,800	–	–
	14 ga. staples	2	15/32	3	2	600	600	860	960	1,060	1,200
				4	3	860	900	1,160	1,295	1,295	1,400
			19/32	3	2	600	600	875	960	1,075	1,200
				4	3	875	900	1,175	1,440	1,475	1,795
Other APA Grades	10d common nails	1-5/8	15/32	3	2	525	725	765	1,010	–	–
				4	2	605	815	875	1,105	–	–
				4	3	765	1,085	1,130	1,195	–	–
			19/32	3	2	650	860	935	1,225	–	–
				4	2	755	965	1,080	1,370	–	–
				4	3	935	1,290	1,365	1,485	–	–
			23/32	3	2	710	955	1,020	1,335	–	–
				4	2	825	1,030	1,175	1,445	–	–
				4	3	1,020	1,400	1,480	1,565	–	–
	14 ga. staples	2	15/32	3	2	540	540	735	865	915	1,080
				4	3	735	810	1,005	1,105	1,105	1,195
			19/32	3	2	600	600	865	960	1,060	1,200
				4	3	865	900	1,130	1,430[5]	1,370[5]	1,485[5]

For SI: 1 inch = 25.4 mm, 1 psf = 0.0479 kN/m^2

(1) Allowable shear values for fasteners in framing members of other species shall be calculated for all grades by multiplying the values for fasteners in Structural I by 0.82, for species with a specific gravity of at least 0.42 but less than 0.49, and by 0.65 for species with a specific gravity of less than 0.42. Allowable shear values noted in the table are for fasteners in framing members having a minimum specific gravity of 0.49.

(2) Fastening along intermediate framing members: Nails must be spaced 12 inches on center, except spacing must be 6 inches on center for spans greater than 32 inches.

(3) Panels must conform to UBC Standard 23-2, UBC Standard 23-3, PS 1-95, PS 2-92 or NER-108.

(4) This table gives shear values for Cases 1 and 2, defined in Table 23-11-H of the code. The values shown are applicable to Cases 3, 4, 5 and 6, provided fasteners at all continuous panel edges are spaced in accordance with the boundary fastener spacing, and provided the maximum shear is limited to 1,200 plf.

(5) Allowable shear value may be increased 60 pounds per foot when 23/32-inch wood structural panels are used.

BACKGROUND

A diaphragm is a large, flat structural unit acting like a deep, thin beam. In plywood diaphragms, the plywood sheathing is the “web” of the beam and the edge framing (chords) are the “flanges” of the beam.

The use of plywood as a shear-resistant material is not new, since the behavior of plywood sheathing used as roof and floor diaphragms has been well established by previous testing and extensive field use.

One of the first investigations was by David Countryman in 1951 *(1)*. This research was directed primarily at establishing the concept that plywood functioned as an efficient shear-resistant diaphragm, and formed a basis for plywood diaphragm design.

Three years later additional research was conducted to expand the knowledge through investigation of the effect of panel layout, blocking, and orientation of the framing and plywood panel joints relative to the load *(2)*.

Nineteen additional diaphragms were tested in 1966 *(3)*. This research reflected changes in the manufacture of plywood due to the promulgation of U.S. Product Standard PS 1-66 *(4)*. Also, other construction variables were evaluated, such as “short” plywood nails, preframed roof panels, and plywood over steel bar joists.

Highlights of the research reported in the above references are included in Appendix A to this report.

In addition to the research done at the facilities of *APA – The Engineered Wood Association,* plywood diaphragms have been tested at other laboratories, particularly the Forest Products Laboratory at Oregon State University. A comprehensive listing of wood and plywood diaphragm tests has been published by the American Society of Civil Engineers *(5)*.

Even with this extensive record of completed research, there were a number of features still remaining to be verified by testing. At the top of the list was the need to test diaphragms capable of resisting loads much larger than those included in currently published tables of recommended shears for plywood diaphragms. One reason for this need was the addition to the Uniform Building Code *(6)* of Seismic Design Zone 4, and greater design accelerations which resulted from investigation following the 1971 San Fernando earthquake.

All of the model building codes allow the calculation of diaphragm strength by the principles of mechanics using fastener strength values and plywood shear values as given by the code. However, there is reluctance by the engineer to make such calculations or the building official to accept such calculations without confirming test data.

OBJECTIVE

The tests reported here were undertaken to develop design and construction recommendations for high diaphragm shears using two layers of plywood, thicker plywood, or a greater number of fasteners than are common in current practice.

Concurrent with the need to develop “high-load” diaphragms was the need to verify that empirical equations, commonly used to calculate diaphragm shears and deflections, are applicable at higher loads.

Secondary objectives of the research were the evaluation of field-glued plywood, diaphragms with openings, use of staples instead of nails, and measurement of chord forces.

TEST SETUP

Diaphragms were loaded laterally using hydraulic cylinders spaced 2 ft o.c., as shown in Figure 1. The cylinders were calibrated individually in a 60,000-lb Tinius Olson testing machine.

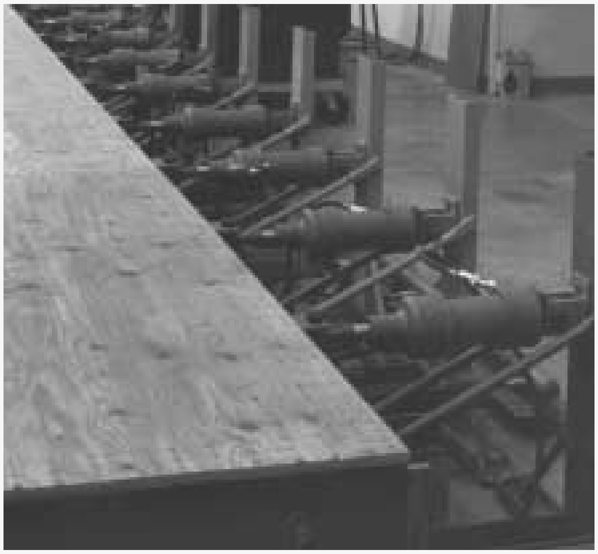
The total lateral load was transferred through load cells to reaction buttresses at the two ends of the tension chord. A buttress and load cell are shown in Figure 2. Each buttress in turn transferred the load to the laboratory structural test floor back through a large-diameter steel pin located nearly in line with the loaded edge of the diaphragm. The pin connection to the laboratory floor allowed the buttresses to move with the diaphragm and not restrict any elongation of the tension chord.

Tension and compression chords of the diaphragms were supported by ball-bearing casters traveling in a track which allowed free lateral deflection, but prevented vertical movement.

Analog signals of loads, pressure, and displacements were converted to digital and printed on a coupled printer for a permanent record. Electronic equipment provided 23 channels of instrumentation.

FIGURE 1

HYDRAULIC CYLINDERS 2 FT o.c. ALONG THE COMPRESSION CHORD.



The data recorded included tension and deflection at the mid-point of the tension chord (see Figure 3), load at each reaction, and pressure of the hydraulic fluid to the loading cylinders. Relative displacement (slip) at panel edge joints, elongation of the tension chord, and the changes in diagonals of the holes in the two diaphragms with openings were also measured and recorded.

TEST PROCEDURE

Diaphragms were tested by applying a uniform load through hydraulic cylinders spaced 24" o.c. The same sequence and duration of loading was used for each test, except Diaphragm 7. The sequence of loading is shown schematically in Figure 4 (page 6).

Before each test, a test load for the diaphragm was estimated (see Design section for each diaphragm). Load was applied to the diaphragm in one-quarter increments of this estimated test load. Each increment was applied and held for ten minutes after which loads and deflections were recorded. This loading sequence continued until the test load was reached. After the test load was reached, the load was released and any residual loads or displacements were recorded after ten minutes at zero

FIGURE 2

TYPICAL DIAPHRAGM UNDER TEST.
The load cell, in the left foreground, measures the end reaction in pounds. The load cell bears on a buttress which is fastened to steel wide-flange beams that are free to move laterally with elongation of the tension chord. The transducers, seen on the plywood sheathing, measure relative displacement between panels at joints.

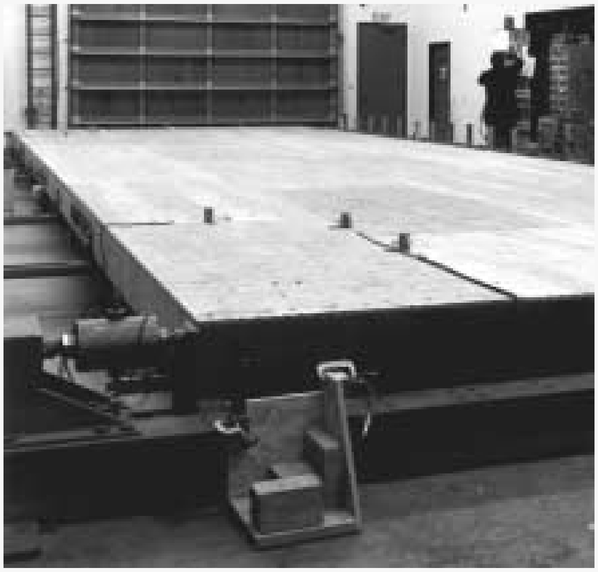
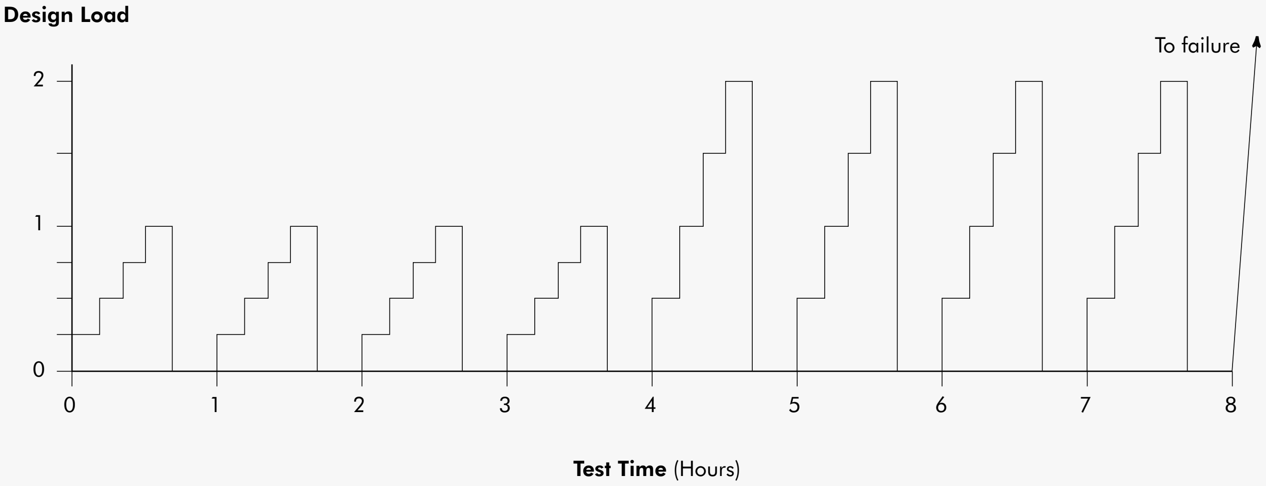


FIGURE 3

TRANSDUCER MEASURING LATERAL DEFLECTION AT THE MID-POINT OF THE TENSION CHORD.
Note also the strain-gaged plate to measure tension force in chord.

FIGURE 4

LOAD APPLICATION vs TIME FOR DIAPHRAGMS 1-6 AND 8-11.



applied load. Each load cycle required exactly one hour. The loading to test load was repeated four times. Load-deflection curves are given in Appendix D.

Following the fourth cycle to test load, the increments were increased to one-half of the test load and the diaphragm loaded from zero to twice test load, again in four equal increments.

After completion of the eighth cycle of loading (8 hours of continuous testing), load was again applied and continued until failure. Data recording during the ultimate-load cycle was limited to deflection at the centerline, load at the two reactions, and hydraulic pressure.

Diaphragm 7 was loaded a total of 12 times before being loaded to ultimate. The first 6 cycles were to the estimated test load, followed by 6 cycles to twice test load. The total time under load testing, prior to ultimate, was the same (8 hours) as the other tests. The 8-hour test schedule was maintained for Diaphragm 7 by reducing the 10-minute hold at each load level to 6 minutes.

MATERIALS AND SPECIMENS

Many materials and construction details were common to all diaphragms tested. These common details are described here, while the sections describing specific diaphragms contain construction details unique for those diaphragms.

The materials used to fabricate the test diaphragms were of commonly available grades and sizes. Exceptions were the 14-ga x 2-3/4"-long staples, which were a recently introduced item, and the 7/8" 4-ft x 10-ft plywood panels used in Diaphragm 11.

Framing

Lumber used for framing was Standard or Construction-grade Douglas-fir. The 2x4s were kiln dried. The larger lumber sizes were graded and surfaced green, but had air dried to a moisture content of 10 to 15%.

Chords

The first ten diaphragms tested were 16 ft x 48 ft. The chords were constructed of nominal 4 x 10 (3-1/2" x 9-1/4" net size) Douglas-fir lumber. A single 16-ft length was used for each 16-ft end chord and four 12-ft lengths were used for the 48-ft tension and compression chords.

Connection details for the diaphragm chords are shown in Figure 5. These details were used for all tests. The 12-ft pieces were spliced with 3/8"-thick x 4"-wide steel plates fastened with 3/4" bolts in single shear. A strain-gaged 1/4"-thick x 4"-wide cold-rolled steel splice plate was used for the center splice of the tension chord (see Figure 3). The chord members were fastened together at the corners of the diaphragm with steel angles. The angles were cut from 4" x 4" x 3/8" steel angle. They were fastened to each chord member with two 3/4" bolts.

The 4 x 10 chord members were inspected after each test and turned over or resurfaced as necessary to provide an undamaged nailing surface for construction of the next diaphragm. No chord members were reduced by resurfacing to less than the size of a nominal 4 x 8 member (3-1/2" x 7-1/4" net size).

Diaphragm 11 was constructed similar to the first ten, except for length. This diaphragm was 50-ft instead of 48-ft long. The change in length made the diaphragm an even multiple of the 10-ft panel length.

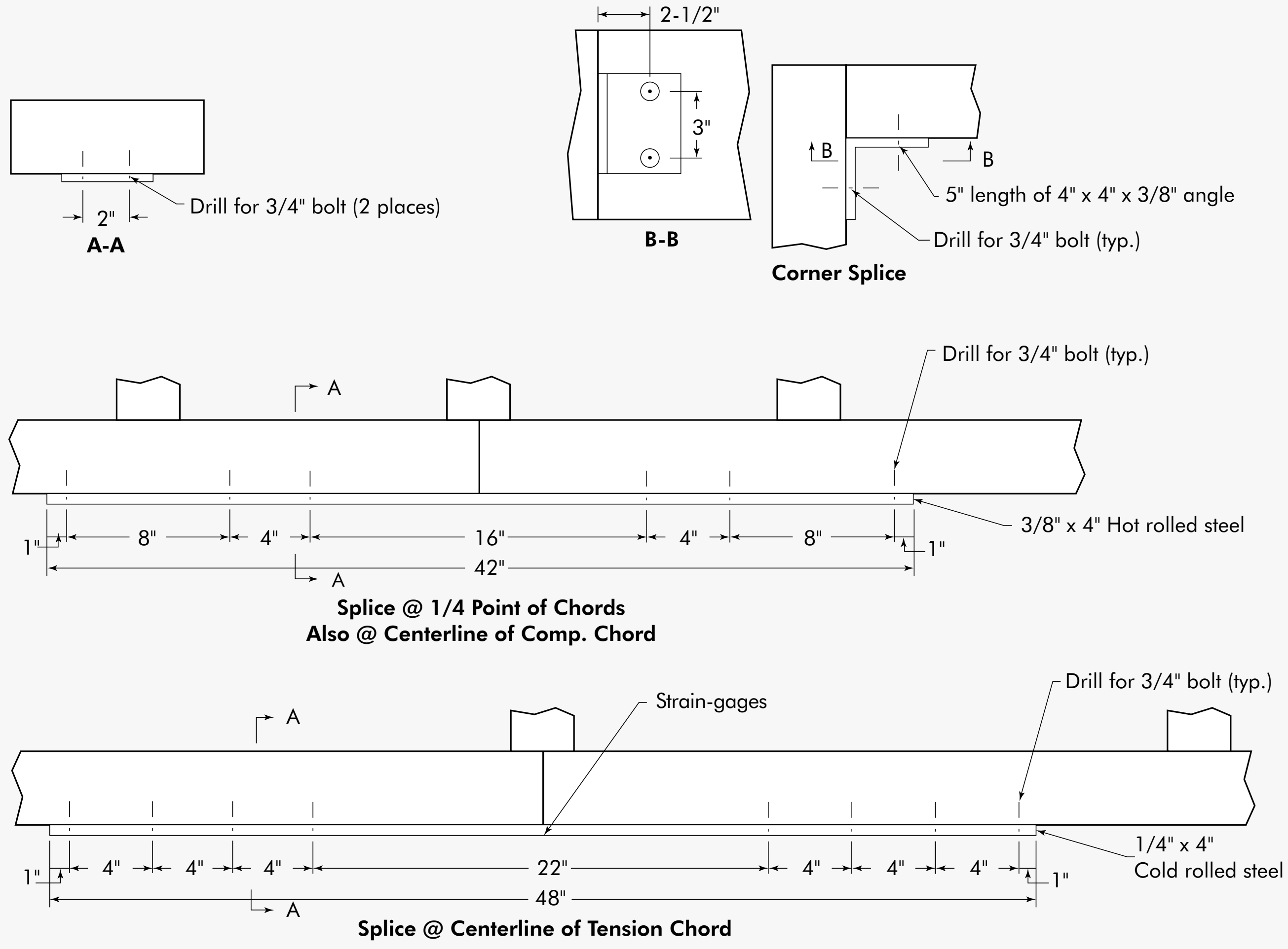
Plywood

All plywood was APA trademarked STRUCTURAL I C-D or C-C, except for Diaphragm 11, and was manufactured in accordance with PS-1 *(14)*. The 7/8"-thick APA trademarked C-D plywood panels used for Diaphragm 11 were 10-ft long. These panels were specifically manufactured for the test, using Group 1 species for the face and back veneers and Group 4 species for all inner plies.

Note: Current nomenclature for APA trademarked C-D and C-C plywood panels is APA Rated Sheathing. C-D panels

FIGURE 5

DIAPHRAGM CHORD DETAILS.



typically are classified Exposure 1 and C-C panels are classified Exterior. Structural I panels are so marked. Applicable plywood panels also include the notation PS 1-95, PS 2-92 or (APA Standard) PRP-108 *(16, 17, 18)* in their trademarks.

Undamaged plywood panels were salvaged from tested specimens and reused on subsequent tests.

In many cases, duplex-head nails were substituted for the common nails listed to facilitate disassembly. Duplex-head nails are equal in diameter to common nails, but 1/4" shorter.

A gap was left between plywood panels at all end and edge joints, in accordance with APA plywood sheathing installation recommendations.

CONTROL DIAPHRAGM – PANELIZED CONSTRUCTION

Diaphragm No. 1

Purpose

Diaphragm 1 was the “control” specimen and was tested to provide a basis for comparison to subsequent tests. These tests added such variables as an extra layer of plywood in high shear areas, openings in the diaphragm, and plywood field-glued to the framing.

Construction

Framing for Diaphragm 1 is typical for panelized roof construction. Plywood was nailed with face grain parallel to 8-ft-long, 2x4 subpurlins spaced 24" o.c. The preframed assemblies of plywood and 2x4 subpurlins were supported by 4x10 purlins spaced 8 ft o.c., which in turn were supported by 5-1/8" x 12" glulams spaced 16 ft o.c. This construction is commonly used for plywood roof diaphragms on commercial and industrial buildings.

Figure 5 (page 7) shows chord details, and Figure 6 shows the framing and panel layout. The layout was chosen to include two continuous joints parallel to the 48-ft length of the diaphragm.

Plywood was 1/2" APA STRUCTURAL I C-D 32/16, fastened with 10d duplex-head common nails. Nail spacing was 4" o.c. along the diaphragm boundary, 6" o.c. at interior panel edges, and 12" o.c. at framing at the interior of the panels.

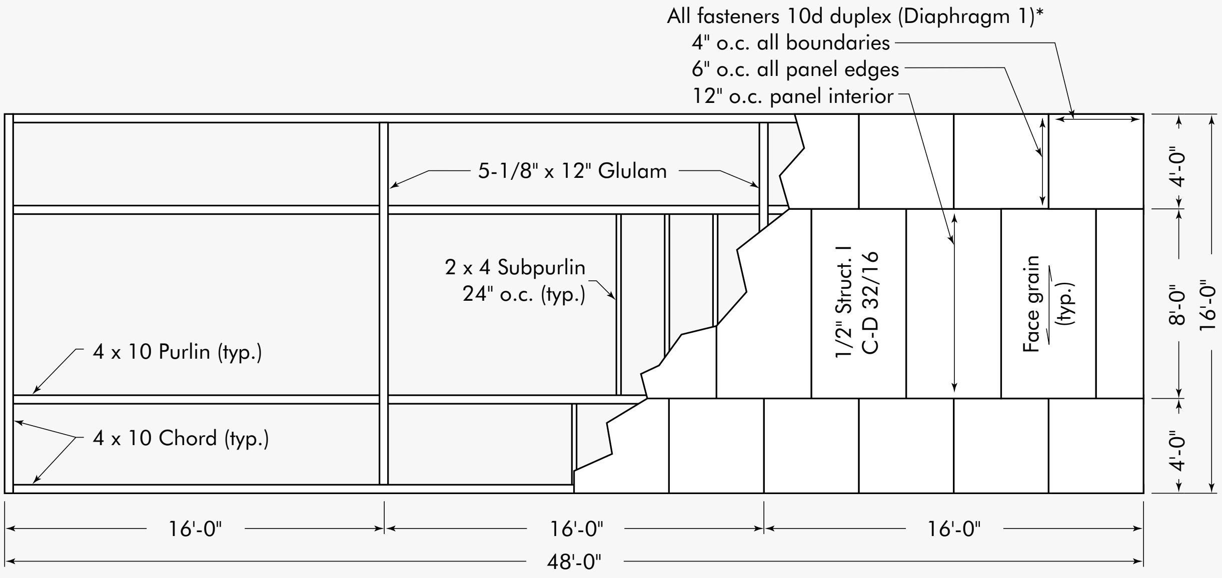
Design

Recommended Design Shear

The recommended design shear for Diaphragm 1 can be found in previously published tables. (See Appendix A.) However, design shear is calculated below as an example of how the tabular values may be obtained.

FIGURE 6

FRAMING DETAILS AND PANEL LAYOUT FOR DIAPHRAGMS NO. 1 AND 5.



*See page 21 for nail schedule used for Diaphragm 5 (field-glued construction).

Allowable load based on plywood shear stress, V_{cp}

$V_{cp} = 190 \times 1.33 \times 12 \times 0.535 = 1{,}622$ plf

effective thickness for shear for 1/2" STRUCTURAL I plywood *(8)*
inches per foot
increase for wind/earthquake load (1.6 maximum) *(8)*
design shear stress for STRUCTURAL I plywood *(8)*

Allowable load based on lateral fastener load at boundary, V_{np}

$V_{np} = 94 \times 1.30 \times 1.33 \times 3 \times 0.89 = 434$ plf

reduction for interior framing less than 3" nominal *(1)*
fasteners per foot
increase for wind/earthquake load *(7)*
increase for diaphragm construction *(7)*
design lateral load for 10d common nails *(7)*

Recommended design shear = 435 plf (rounded to the nearest 5 plf), limited by fasteners at boundary. (Code acceptance for this construction is for a design shear of 425 plf. This value was derived from fastener design loads accepted through 1961 [120 x 1.33 x 3 x 0.89 = 425 plf].)

Note: The allowable lateral load for nails, and adjustment factors for load duration (C_D) and diaphragms (C_{di}), have been revised in the current edition of the National Design Specification for Wood Construction *(19)*. Also, the lateral load for nails is based on penetration into the framing of 12 x the nail diameter, whereas these and past APA test specimens have been fabricated with nails having penetration based on 11 x the nail diameter (for Douglas-fir framing). APA diaphragm tests demonstrate an adequate margin of shear strength (e.g. load factor) when nailed sheathing connections provided penetration of 11 x the nail diameter. V_{np} changes about -3% if the revised values are used:

$V_{np} = 90 \times 1.1 \times 1.6 \times 3 \times 0.89 = 423$ plf

Deflection

Diaphragm deflection *(1, 9)*, $\Delta =$

$$\frac{5VL^3}{8EAb} + \frac{VL}{4Gt} + 0.188\,Le_n + \frac{\Sigma(\Delta_c X)}{2b}$$

deflection due to chord splice slip
deflection due to nail slip
shear deflection
bending deflection

where V = shear (plf)

L = diaphragm length (ft)

b = diaphragm width (ft)

A = area of chord cross section (in.^{2})

E = elastic modulus of chords (psi) from National Design Specification *(7, 19)*. For use in this formula, "E" values listed in the lumber standards should be increased by 3%, since shear deflection is separately calculated. This 3% restores the usual reduction included in tabulated E values to account for shear deflection *(7, 19)*.

G = shearing modulus of the webs (psi) from Plywood Design Specification *(8)*.

t = effective plywood thickness for shear (in.) from Plywood Design Specification *(8)*.

e_n = nail deformation (in.) from Appendix Table B-4 at calculated load per nail on perimeter of interior panels, based on shear per foot divided by number of nails per foot. If the nailing is not the same in both directions, use the greater spacing for calculations.

$\Sigma(\Delta_c X)$ = sum of individual chord-splice slip values (in.) on both sides of the diaphragm, each multiplied by its distance (ft) to the nearest support.

For Diaphragm 1, deflection is calculated for a shear of 425 plf, since this was the test load used in the first four loading cycles, when deflection was measured.

Load per nail at interior panel edges = 425/2 = 212 lb

$$e_n = \left(\frac{212}{769}\right)^{3.276} = 0.0147 \text{ in.}$$

Chord joint slip (estimated from test data):

Tension chord: 0.011" at 1/4 point; 0.015" at center

Compression chord: 0.002" at 1/4 point; 0.002" at center

$$\Delta = \frac{5(425)(48^3)}{8(1.7 \times 10^6 \times 1.03)(32.375)(16)}$$

$$+ \frac{425(48)}{4(90000)(.535)} + .188(48)(.0147)$$

$$+ \frac{(2 \times .011 \times 12)+(.015 \times 24)+(2 \times .002 \times 12)+(.002 \times 24)}{2(16)}$$

$$= 0.032 + 0.106 + 0.133 + 0.023 = 0.294 \text{ in.}$$

Test Results and Discussion

Midpoint deflection, measured at the test load of 425 plf shear, was 0.312" on the first cycle, which is very close to the 0.294" calculated deflection.

The test on Diaphragm 1 was stopped at 1788 plf shear when the hydraulic cylinders at the midpoint of the diaphragm reached their maximum extension. However, failure was imminent because of fastener slip occurring at the 8-ft plywood joint located 2 ft from the end of the diaphragm. Visual inspection indicated that the nails in this area were starting to withdraw from the lumber framing. The 1788 plf shear corresponds to a load factor of 4.11+ based on the calculated design shear of 435 plf (4.21+ based on published 425 plf).

HIGH-LOAD DIAPHRAGM – TWO-LAYER PANELIZED CONSTRUCTION

Diaphragm No. 2

Purpose

This diaphragm was tested to determine the strengthening effect of adding a second layer of plywood to the high shear areas at each end of the diaphragm.

Construction

Diaphragm 2 was identical to Diaphragm 1 except that an additional layer of 1/2" APA STRUCTURAL I C-D 32/16 plywood was fastened over the top of the first layer in the high shear area at each end of the diaphragm. Construction details of the chords are shown in Figure 5 (page 7) and the framing and panel layout in Figure 7. The second layer extended 13 ft (approximately one-quarter span) from each end of the diaphragm. The plywood in the top layer was located with all edge joints having a 1-ft minimum offset from any framing member supporting the bottom layer, except at the boundary.

Plywood for the top layer was attached with 14-ga x 1-3/4"-long staples spaced 3" o.c. along all panel edges except boundary edges, and on a 12" grid in the panel interior. The panel edges that occurred over the diaphragm chords were fastened with 10d nails spaced 4" o.c.

The offset of the top layer, as well as the length of staples for the top layer, were selected so that penetration into framing would not be a factor in the shear resistance developed. In this way, such construction could be used to upgrade existing roofs where framing location sometimes cannot be accurately determined.

Design

Recommended Design Shear

Fastener schedules for the top layer and the bottom layer of plywood each conform to previously established design factors for “lightly loaded” diaphragms (see Appendix A) for which boundary fastening controls. In this case, fastening at interior panel joints is reduced one-third for Case 1 or Case 2 blocked diaphragms. Therefore, checks need be made only of boundary fastening and, for this two-layer diaphragm, of plywood shear stress.

Allowable load based on plywood shear stress, V_{cp}

The bottom layer of plywood alone must resist full diaphragm design shear. This is because the joints in the top layer do not occur over framing members and all shear at the top layer joints is resisted only by the bottom layer of plywood.

$V_{cp} = 1622$ plf (see Diaphragm 1)

Allowable load based on lateral fastener load at boundary, V_{np}

Reduction for close nail spacing is not required since 4x chord members allow multiple rows of nails.

$$V_{np} = 94 \times 1.30 \times 1.33 \times \underset{\text{fasteners per foot (3 from each layer)}}{6} \times 0.89 = 868 \text{ plf}$$

Recommended design shear = 870 plf (rounded to the nearest 5 plf), limited by fasteners at boundary.

Note: The allowable lateral load for nails, and adjustment factors for load duration (C_D) and diaphragms (C_{di}), have been revised in the current edition of the National Design Specification for Wood Construction *(19)*. Also, the lateral load for nails is based on penetration into the framing of 12 x the nail diameter, whereas these and past APA test specimens have been fabricated with nails having penetration based on 11 x the nail diameter (for Douglas-fir framing). APA diaphragm tests demonstrate an adequate margin of shear strength (e.g. load factor) when nailed sheathing connections provided penetration of 11 x the nail diameter. V_{np} changes about -3% if the revised values are used:

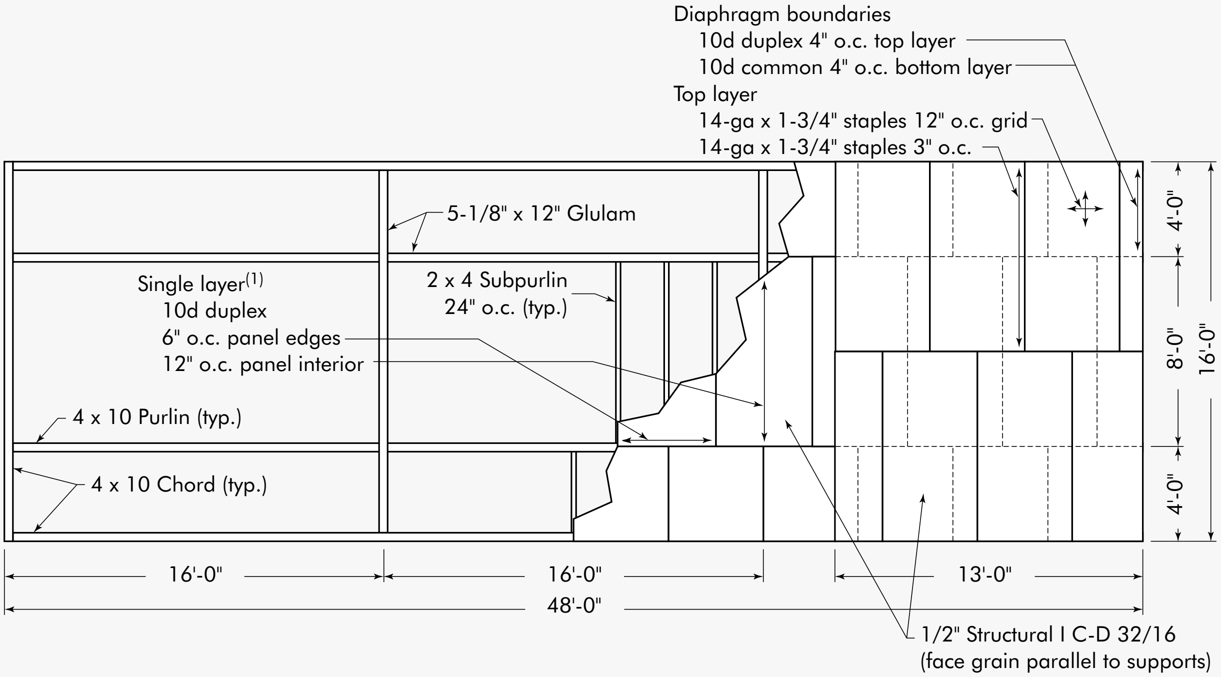
$$V_{np} = 90 \times 1.1 \times 1.6 \times 6 \times 0.89 = 846 \text{ plf}$$

Deflection

The equation for calculating diaphragm deflection cannot be used for a two-layer diaphragm.

FIGURE 7

FRAMING DETAILS AND PANEL LAYOUT FOR DIAPHRAGM NO. 2.



(1) Bottom layer (at diaphragm ends): 10d common 6" o.c. panel edges, 12" o.c. panel interior.

Test Results and Discussion

Midpoint deflection, measured at the test load of 850 plf shear, was 0.421" on the first cycle.

Ultimate load was 3456 plf, for a load factor of 3.97. This indicates the strength of the two-layer system. Failure occurred when the plywood sheared from the 16-ft end chord. The nail heads pulled through the lower layer and the top-layer fasteners withdrew from the chord. Penetration of the nails attaching the top layer to the chords was reduced by the bottom layer of 1/2" plywood, and an additional 1/4" by the duplex head on the nails. However, even with both of these reductions, penetration into the lumber slightly exceeded the 1-5/8" minimum required by building codes.

Diaphragm 2 indicated that a two-layer diaphragm is feasible for high loads. To provide conservative results, care was taken during construction of this diaphragm to be certain that none of the plywood joints in the top layer occurred over framing members. In certain applications, such as reroofing or structurally upgrading existing diaphragms, it may be impossible to determine the locations of the framing members supporting the existing roof. Hence, the conservative approach used in this test has general application to all roofing installations where a second (overlying) layer is installed. Since there was no framing under the plywood edge joints, the staples fastening the top layer of plywood penetrated only through the bottom layer of 1/2" plywood.

The strength added by the stapled top layer of plywood was substantially greater than would be expected. Previous research *(10, 11)* verifies that the composite action of two shear-resisting elements can result in an assembly that is greater in strength than the sum of the elements acting separately.

HIGH-LOAD DIAPHRAGMS – CONVENTIONAL CONSTRUCTION

Diaphragm No. 7

Purpose

This diaphragm was tested to determine if a large number of fasteners would result in a corresponding increase in diaphragm strength. In addition, staples were substituted for nails to determine if staples would be less prone to split narrow framing than closely spaced nails equivalent in strength.

Construction

Diaphragm 7 was constructed using 14-ga x 1-3/4"-long staples to attach the 5/8" APA STRUCTURAL I C-D 42/20* plywood to wood I-joists spaced 32" o.c. The flanges of the I-joists were 1-1/2" deep x 2-5/16" wide laminated veneer lumber (LVL). The large number of staples necessary to develop the high shear at the diaphragm ends were distributed into three rows (spaced 2" o.c. in each row, total 18 per foot) at the perimeter chord and two rows (spaced 2" o.c. in each row, total 12 per foot) at panel edges over interior framing.

Blocking for the plywood edge joints perpendicular to the I-joists was provided by placing 2x4s with the wide face horizontal. The blocking was held in place by attaching a "Z" framing anchor to each end, as shown in Figure 8. Figure 9 shows details of framing and panel layout.

*Span Rating now redesignated to 40/20.

Design

Recommended Design Shear

Allowable load based on plywood shear stress, V_{cp}

$$V_{cp} = 190 \times 1.33 \times 12 \times 0.707 = 2{,}144 \text{ plf}$$

effective thickness for shear for 5/8" STRUCTURAL I plywood *(8)*

Allowable load based on lateral fastener load at Boundary, V_{np}

design lateral load for 14-ga staples *(12)*

fastener penetration into framing

$$V_{np} = 75 \times 1.33 \times 18 \times \underline{(1.125/4 + 0.50)} = 1403 \text{ plf}$$

reduction for penetration less than 2" (see Appendix B)

fasteners per foot (6 from each row)

FIGURE 8

DIAPHRAGM 7 UNDER CONSTRUCTION SHOWING WOOD I-JOISTS SPACED 32 IN. o.c. AND 2x4 FLAT BLOCKING.

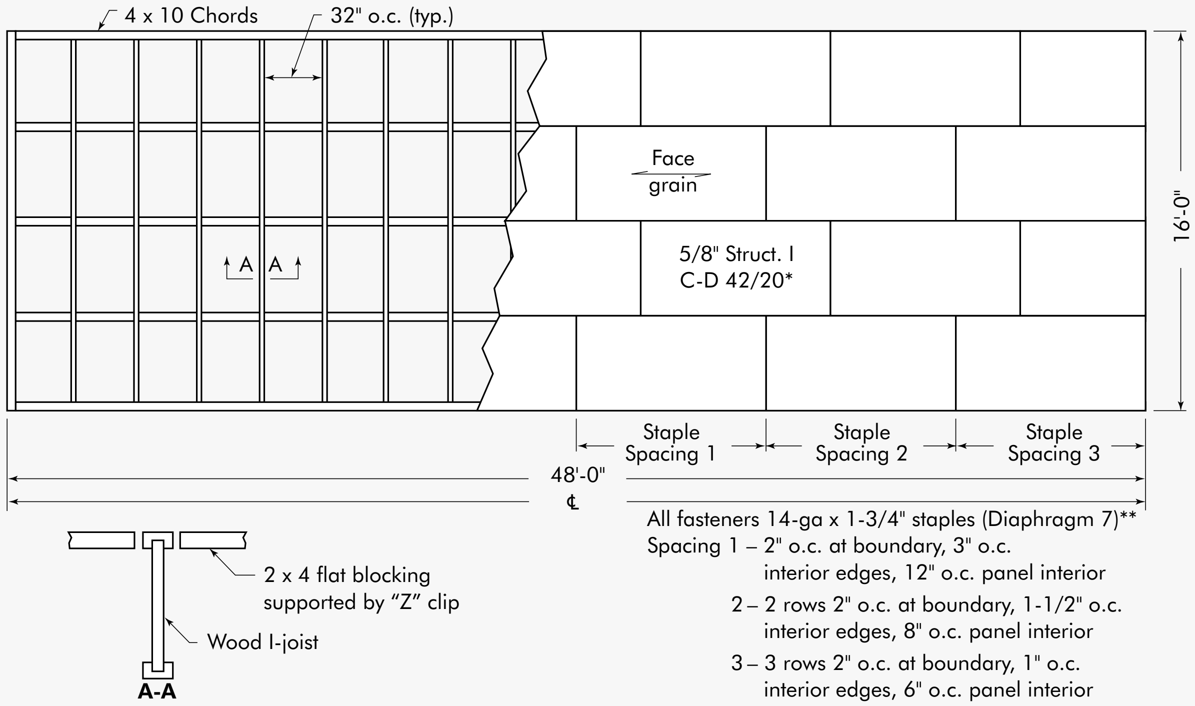
Note: The allowable lateral load for nails, and adjustment factors for load duration (C_D) and diaphragms (C_{di}), have been revised in the current edition of the National Design Specification for Wood Construction *(19)*. However, when sheathing is fastened to framing with *staples* (Diaphragm Nos. 7, 8 and 11), test results indicate that a wind/earthquake load duration factor (C_D) of 1.33 provides comparable margin of strength (e.g., load factor) as obtained in tests of nailed diaphragms; also, the diaphragm factor (C_{di}) is not considered applicable for stapled sheathing connections, as discussed in Appendix B.

Allowable load at discontinuous interior panel joints

To check design shear due to reduced interior edge fastening in high-load diaphragms, load must be adjusted such that shear deflection and fastener deformation of the jointed plywood panel is equivalent to shear deflection of the continuous panel. This will require trial to determine if use of full fastener load causes the calculated shear in the continuous panel to exceed

FIGURE 9

FRAMING DETAILS AND PANEL LAYOUT FOR DIAPHRAGMS 6 AND 7.



*Now 40/20

**See page 23 for nail schedule used for Diaphragm 6 (field-glued construction)

its allowable design shear. (If so, the fastener load is adjusted downward to correspond with plywood design shear.) Derivation of the following formula appears in Appendix C.

$$V_{cp} = nV_n + \frac{24tGe_n}{\ell}$$

where V_{cp} = design shear (plf)

n = fasteners per foot

V_n = fastener design load (lb)

ℓ = support spacing (in.)

other terms as previously defined.

$V_n = 75 \text{ x } 1.33 \text{ x } (1.125/4 + 0.50) = 78$ lb

e_n for 14-ga staple with penetration less than 2" (from Appendix Table B-4) is assumed for dry/dry conditions to correspond with test.

$$e_n = \left(\frac{78}{596}\right)^{1.999} = 0.0172 \text{ in.}$$

$$V_{cp} = (12 \text{ x } 78) + \frac{24 \text{ x } .707 \text{ x } 90000 \text{ x } .0172}{32}$$

$$= 1757 \text{ plf} < 2144 \text{ plf}$$

Design shear (average of continuous panel and panel with stapled butt joint),

$$V = \frac{1757 + (78 \text{ x } 12)}{2} = 1347 \text{ plf}$$

Recommended design shear = 1345 plf (rounded to the nearest 5 plf), limited by shear capacity at interior panel joints.

Note that the shear value for reduced fastener penetration cannot be interpolated from Table 1. This is true any time the design is limited by the shear capacity at interior joints.

Deflection

Deflection is calculated for a shear of 1325 plf, since this was the test load used in the first six loading cycles, when deflection was measured.

The fastener slip constant is 0.376 for the case where fastener spacing is increased as shear decreases toward the interior of the diaphragm. The ratio between shear load and fasteners per foot is assumed to be uniform, which is a reasonable approximation for the “step” change in fastener spacing normally used in construction.

Load per staple (at interior panel edges) = 1325/12 = 110 lb

$$e_n = \left(\frac{110}{596}\right)^{1.999} = 0.0341 \text{ in.}$$

Chord joint slip (estimated from test data):

Tension chord: 0.027" at 1/4 point; 0.036" at center
Compression chord: 0.004" at 1/4 point; 0.005" at center

$$\Delta = \frac{5(1325)(48^3)}{8(1.7 \times 10^6 \times 1.03)(32.375)(16)}$$

$$+ \frac{1325(48)}{4(90000)(.707)} + 0.376(48)(.0341)$$

$$+ \frac{(2 \times .027 \times 12)+(.036 \times 24)+(2 \times .004 \times 12)+(.005 \times 24)}{2(16)}$$

$$= 0.101 + 0.250 + 0.615 + 0.054$$

$$= 1.020 \text{ in.}$$

Test Results and Discussion

Prior to the construction of Diaphragm 7, tests were conducted to study the fastener type and spacing required to develop high loads. Specimens consisted of an 8" x 16" piece of plywood fastened to framing identical to the top flange of the I-joists. During these tests it was discovered that a large number of either 10d or 16d nails, spaced less than 3" o.c. as required to develop high shears, often caused the framing member to split. On the other hand, the use of pneumatically driven staples showed that staples with a 7/16" crown could be driven as close as 1" o.c. without causing splitting, either at the time of driving or when the specimen was loaded in shear.

Diaphragm 7 test results indicated that staples are practical for high-load diaphragms. This diaphragm reached an ultimate load of 3925 plf for a load factor of 2.92. Failure occurred in the highly stressed area 4 ft from one end when the high shear in the plywood caused it to buckle upward pulling the staples from the 2x4 blocking. This was followed immediately by shearing of the edges of several panels from blocking or framing. In all cases, the failure was staple withdrawal from the framing. The failure area of Diaphragm 7 is shown in Figure 10.

Midpoint deflection at a test shear of 1325 plf was 0.588" on the first cycle, which is about 7/16" less than the 1.020" calculated deflection. The polymer coating on the staples may have been responsible for the lower-than-expected measured deflection.

Number 7 was the only diaphragm subjected to 12 cycles of loading before being tested to ultimate. The purpose of the additional cycles was to determine if increasing the repetitions of load would increase maximum deflection and/or set.

Examination of the load-deflection data indicated no significant increases after the third repetition to the same load.

Correlation with Table 1 Values

Diaphragm 7: 14-ga staples at 2" o.c. – 3 rows (18 staples per foot) at boundary and 2" o.c. – 2 rows (12 staples per foot) at interior joints.

The tabulated design shear corresponding to this schedule is 1440 plf. This value is based on 3/4" STRUCTURAL I plywood over supports 48" o.c. with 2" staple penetration, which controls the tabulated shear. The calculated design shear for 5/8" STRUCTURAL I plywood would be 1541 plf for a 32" span if the full 2" of staple penetration were achieved.

FIGURE 10

DIAPHRAGM 7 AFTER FAILURE.

Diaphragm No. 8

Purpose

This diaphragm was tested to determine the effect of increasing the staple penetration into the framing to a 2" minimum, based on results of fastener tests (see Appendix B). Also tested was the performance of staples with 3/4"-thick plywood.

Construction

The 3/4" APA STRUCTURAL I C-D 48/24 plywood was placed over 4-in. nominal framing members, spaced 48" o.c. Blocking for the plywood edges perpendicular to the joists was 4x4 lumber. Figure 11 shows details of the framing and panel layout.

The plywood in Diaphragm 8 was fastened with 14-ga electro-galvanized staples. The staples in one half of the diaphragm were 2-3/4" long and polymer-coated. The staples in the other half were 3" long and not coated. The fastener spacing schedule is shown in Figure 11.

Design

Recommended Design Shear

Allowable load based on plywood shear stress, V_{cp}

$$V_{cp} = 190 \times 1.33 \times 12 \times 0.739 = 2241 \text{ plf}$$

effective thickness for shear for
3/4" STRUCTURAL I plywood (8)

Allowable load based on lateral fastener load at boundary, V_{np}

$$V_{np} = 75 \times 1.33 \times 24 = 2394 \text{ plf}$$

fasteners per foot (8 from each row)

Allowable load at discontinuous interior panel joints

$$V_n = 75 \times 1.33 = 100 \text{ lb}$$

$$e_n = \left(\frac{100}{461}\right)^{2.776} = 0.0144 \text{ in.}$$

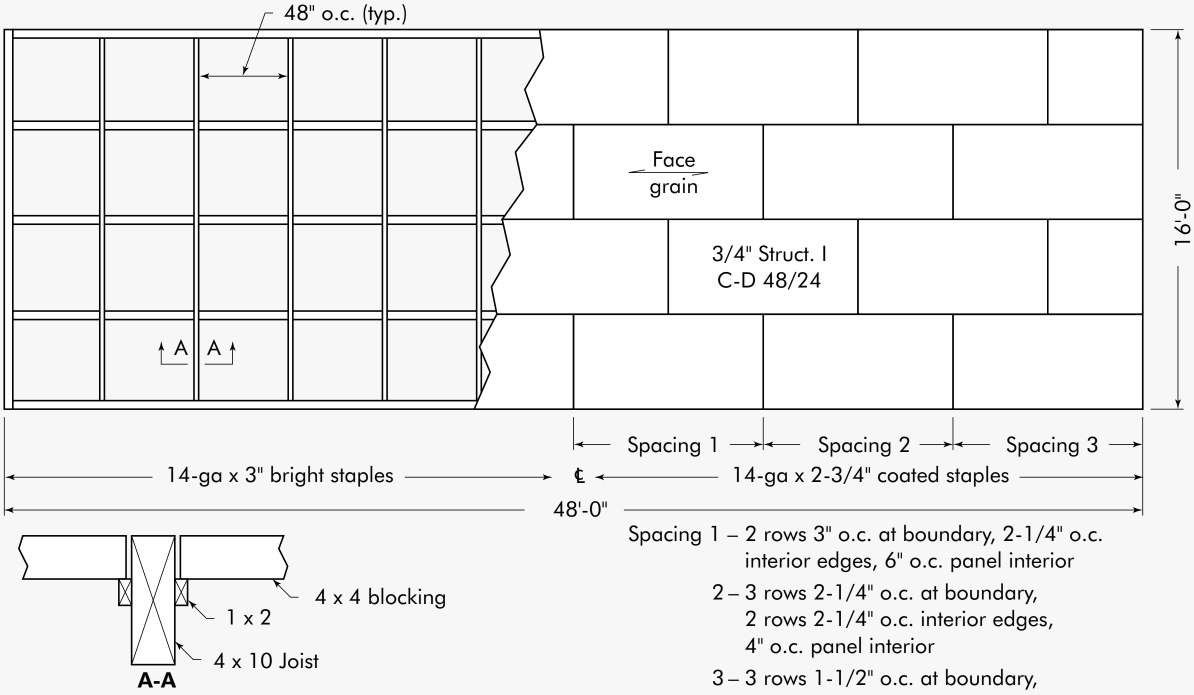
$$V_{cp} = (16 \times 100) + \frac{24 \times .739 \times 90000 \times .0144}{48}$$

$$= 2079 \text{ plf} \leq 2241 \text{ plf}$$

$$\text{Design shear, } V = \frac{2079 + (100 \times 16)}{2} = 1839 \text{ plf}$$

FIGURE 11

FRAMING DETAILS AND PANEL LAYOUT FOR DIAPHRAGM 8.



Spacing 1 – 2 rows 3" o.c. at boundary, 2-1/4" o.c. interior edges, 6" o.c. panel interior

2 – 3 rows 2-1/4" o.c. at boundary, 2 rows 2-1/4" o.c. interior edges, 4" o.c. panel interior

3 – 3 rows 1-1/2" o.c. at boundary, 2 rows 1-1/2" o.c. interior edges, 3" o.c. panel interior

Recommended design shear (at boundary) = 1840 plf (rounded to the nearest 5 plf), limited by shear capacity at interior panel joints.

Deflection

Deflection is calculated for a shear of 1760 plf, since this was the test load used in the first four loading cycles, when deflection was measured.

Load per staple (at interior panel edges) = 1760/16 = 110 lb

$$e_n = \left(\frac{110}{461}\right)^{2.776} = 0.0187 \text{ in.}$$

Chord joint slip (estimated from test data):

Tension chord: 0.035" at 1/4 point; 0.047" at center
Compression chord: 0.005" at 1/4 point; 0.007" at center

$$\Delta = \frac{5(1760)(48^3)}{8(1.7 \times 10^6 \times 1.03)(32.375)(16)}$$

$$+ \frac{1760(48)}{4(90000)(.739)} + 0.376(48)(.0187)$$

$$+ \frac{(2 \times .035 \times 12) + (.047 \times 24) + (2 \times .005 \times 12) + (.007 \times 24)}{2(16)}$$

$$= 0.134 + 0.318 + 0.337 + 0.071 = 0.860 \text{ in.}$$

Test Results and Discussion

Midpoint deflection at a test load of 1760 plf was 0.770" on the first test cycle, which is within 1/10" of the 0.860" calculated deflection.

The initial failure of Diaphragm 8 occurred during the seventh load cycle, which was the third cycle to twice the estimated design load. Immediately upon reaching twice the design test load, the 4x10 chord at one end of the diaphragm failed in compression bearing at the load cell. The diaphragm was immediately unloaded and the 4x10s at each end were reinforced by bolting 1/2"-thick x 4"-wide steel plates to both sides.

After the chords were reinforced at the reaction end, the diaphragm was reloaded for an abbreviated eighth load cycle. The load was held for the 10-minute period and the transducers read only at design load and twice design load.

Following the eighth cycle, the diaphragm was loaded to ultimate. At a shear of 5234 plf (corresponding to a load factor of 2.85+ based on controlling diaphragm shear capacity at interior joints), one of the 1/2" lag bolts fastening the compression chord to its roller-equipped hold-down bent and pulled from the chord. This loss of restraint caused the entire corner of the diaphragm to rise, as shown in Figure 12.

FIGURE 12

DIAPHRAGM 8 AFTER THE FASTENER CONNECTING THE VERTICAL HOLD-DOWN TO THE COMPRESSION CHORD FAILED.

The ultimate shear was not reached for the plywood, staples, or framing since the failure was due to an inadequate hold-down. Examination of the diaphragm after the failure in the test setup revealed only very slight staple withdrawal, which was limited to an area that received a surge of shear load when the corner deflected upward. The plywood and staples appeared to be still capable of resisting a much higher load.

While the hold-down failure emphasizes the uplift force present in a loaded diaphragm, it should not be considered as a critical weakness. In the test diaphragm, the lag screw that failed in the hold-down at this location was resisting the uplift from the end chord in addition to the uplift generated in the tributary length of the compression chord. In normal construction, the connections provided to transfer the shear from the end chord to the shear wall would also provide resistance to uplift. In addition, transfer of shear along the entire length of shear wall at the end of the diaphragm would prevent the buildup of the large concentrated load that caused the initial bearing failure of the end chord during the seventh load cycle.

Correlation with Table 1 Values

Diaphragm 8: 14-ga staples at 1-1/2" o.c. – 3 rows (24 staples per foot) at boundary and 1-1/2" o.c. – 2 rows (16 staples per foot) at interior joints.

The tabulated design shear closest to this schedule is 1800 plf.

Diaphragm No. 9

Purpose

Diaphragm 9 was tested to determine the performance of diaphragms fabricated with multiple rows of power-driven nails.

Construction

The framing, plywood, and plywood panel layout were identical to Diaphragm 8; however, the plywood was fastened with nails instead of staples. See Figure 13 for details.

The plywood was fastened to the framing with pneumatically-driven 10d "short" nails. The actual nail dimensions were 0.148" diameter x 2-1/4" long. In the high shear areas, the 12 nails per foot along the boundary were placed in 3 rows. The 8 nails per foot along interior panel edges were placed in 2 rows. As in other tests, fastener spacing was increased as shear decreased, as shown in Figure 13.

Design

Recommended Design Shear

Allowable load based on plywood shear stress, V_{cp}

V_{cp} = 2241 plf (see Diaphragm 8)

Allowable load based on lateral fastener load at boundary, V_{np}

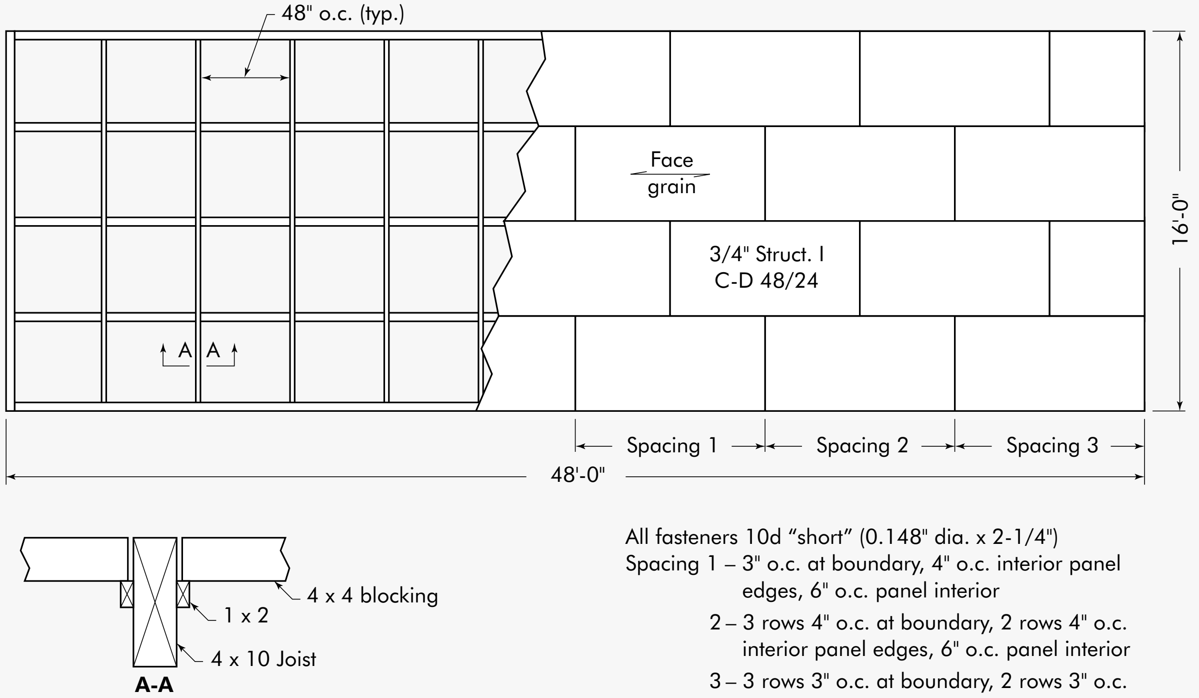
$$V_{np} = 94 \times 1.30 \times 1.33 \times 12 \times \underbrace{(1.5/1.625)}_{\text{reduction for reduced penetration (1.625" required for Group II lumber (7))}} = 1{,}800 \text{ plf}$$

Note: The allowable lateral load for nails, and adjustment factors for load duration (C_D) and diaphragms (C_{di}), have been revised in the current edition of the National Design Specification for Wood Construction *(19)*. Also, the lateral loads for nails are based on penetration into the framing of 12 x the nail diameter, whereas this test specimen was fabricated with 10d "short" (diaphragm) nails having penetration of 1.5", or slightly less than 11 x the nail diameter (1.625" for 10d common nails in Douglas-fir framing). However, past APA diaphragm tests have demonstrated an adequate margin of shear strength (e.g., load factor) when nailed sheathing connections provided penetration of 11 x the nail diameter. V_{np} changes about +4% if the revised values are used, mainly because the allowable lateral load for 10d common nails increases from 90 lb per nail for 1/2"-thick plywood (e.g., side member) to 105 lb when 3/4"-thick plywood is used *(19)*:

$$V_{np} = 105 \times 1.1 \times 1.6 \times 12 \times [1.5/(12)(0.148)] = 1873 \text{ plf}$$

FIGURE 13

CONSTRUCTION DETAILS FOR DIAPHRAGMS 9 AND 10.



All fasteners 10d "short" (0.148" dia. x 2-1/4")
Spacing 1 – 3" o.c. at boundary, 4" o.c. interior panel edges, 6" o.c. panel interior
2 – 3 rows 4" o.c. at boundary, 2 rows 4" o.c. interior panel edges, 6" o.c. panel interior
3 – 3 rows 3" o.c. at boundary, 2 rows 3" o.c. interior panel edges, 6" o.c. panel interior

Allowable load at discontinuous interior panel joints

$$V_n = 94 \times 1.30 \times 1.33 \times (1.5/1.625) = 150 \text{ lb}$$

$$e_n = \left(\frac{150}{769}\right)^{3.276} = 0.0047 \text{ in.}$$

$$V_{cp} = (8 \times 150) + \frac{24 \times .739 \times 90000 \times .0047}{48}$$

$$= 1356 \text{ plf} \leq 2241 \text{ plf}$$

$$\text{Design shear, } V = \frac{1356 + (150 \times 8)}{2} = 1278 \text{ plf}$$

Recommended design shear (at boundary) = 1280 plf (rounded to the nearest 5 plf), limited by shear capacity at interior panel joints.

Note: Based on the allowable lateral load values for nails in the current edition of the National Design Specification for Wood Construction *(19)*, V = 1338 plf if 10d common "short" (diaphragm) nails are used (0.148" diameter x 2-1/4" long).

Deflection
Deflection is calculated for a shear of 1800 plf, since this was the test load used in the first four loading cycles, when deflection was measured.

Load per nail (at interior panel edges) = 1800/8 = 225 lb

$$e_n = \left(\frac{225}{769}\right)^{3.276} = 0.0178 \text{ in.}$$

Chord joint slip (estimated from test data):

Tension chord: 0.117" at 1/4 point; 0.156" at center
Compression chord: 0.017" at 1/4 point; 0.022" at center

$$\Delta = \frac{5(1800)(48^3)}{8(1.7 \times 10^6 \times 1.03)(32.375)(16)}$$

$$+ \frac{1800(48)}{4(90000)(.739)} + 0.376(48)(.0178)$$

$$+ \frac{(2 \times .117 \times 12) + (.156 \times 24) + (2 \times .017 \times 12) + (.022 \times 24)}{2(16)}$$

$$= 0.137 + 0.325 + 0.321 + 0.234 = 1.017 \text{ in.}$$

Test Results and Discussion
The midpoint deflection was 1.192" at a test load of 1800 plf on the first cycle (compared to 1.017" calculated). The nail slip value used in calculating deflection assumes 1-5/8" or greater penetration for the 10d nails. The reduced penetration of the nails in this diaphragm may have increased the nail slip.

Prior to testing of Diaphragm 9, the hold-downs located 40" from each end of the compression chord were rebuilt and load cells added to measure uplift in pounds. The measured average uplift force was 750 lb at the test load of 1800 plf and 1700 lb at a load of 3600 plf, during the eight cycles of test loading.

At a shear of approximately 4200 plf, one of the 16-ft end chords started to fail in column bending due to the high compressive load. The bending of the chord increased the uplift. The test was terminated at a shear load at the boundary of 4668 plf, which corresponds to a load factor of 3.65+ based on the controlling diaphragm shear capacity of 1280 plf at interior joints. At this shear, the uplift force was 3260 lb and the hold-down was failing.

In typical building construction, the roof diaphragm is supported around its entire perimeter by walls. The connection of the roof diaphragm to a wall would have prevented the compression buckling that resulted in the failure in the end chord of Diaphragm 9.

Correlation with Table 1 Values
Diaphragm 9: 10d common x 2-1/4"-long nails at 3" o.c. – 3 rows (12 nails per foot) at boundary and 3" o.c. – 2 rows (8 nails per foot) at interior joints.

The tabulated design shear corresponding to this schedule is 1410 plf. The test diaphragm design shear is less due to reduced nail penetration.

Diaphragm No. 10

Purpose
Diaphragm 10 was identical to Number 9. This diaphragm was tested in an attempt to obtain a failure in the plywood or fastener portions of the diaphragm. The framing would not be expected to fail in a typical building when a plywood roof diaphragm is attached to walls around its perimeter.

Construction
See Diaphragm 9.

Design
Recommended Design Shear
Recommended design shear (at boundary) = 1280 plf, limited by shear capacity at interior panel joints (see Diaphragm 9).

Deflection

The deflection calculations for Diaphragm 10 are identical to those for Diaphragm 9 except for the portion of deflection due to chord joint slip. The chord length measurements during the test indicate the following joint slip:

Tension chord: 0.056" at 1/4 point; 0.075" at center
Compression chord: 0.008" at 1/4 point; 0.011" at center

(Reduced slip in Diaphragm 10 compared to Diaphragm 9 may indicate that slack was removed from bolted joints in the earlier test.)

$$\frac{\Sigma(\Delta_c X)}{2b} =$$

$$\frac{(2 \times .056 \times 12) + (.075 \times 24) + (2 \times .008 \times 12) + (.011 \times 24)}{2(16)}$$

$= 0.113$ in.

$\Delta = 0.137 + 0.325 + 0.321 + 0.113 = 0.896$ in.

Test Results and Discussion

The midpoint deflection was 1.108" at a test shear load of 1800 plf on the first cycle (compared to 0.896" calculated). As noted in Diaphragm 9, reduced nail penetration may have increased nail slip.

Diaphragm 10 failed at a boundary shear of 4946 plf, which corresponds to a load factor of 3.86 based on the controlling diaphragm shear capacity along interior panel joints. Failure was in shear through an 8-ft plywood panel at a point 4 ft from the end of the diaphragm.

The plywood shear-through-the-thickness failure in Diaphragm 10 was the first ever recorded during APA testing of diaphragms. Previous to these tests, the highest ultimate boundary shear load reached in a plywood diaphragm was 2960 plf *(3)*. Since design shear through-the-thickness for 15/32" through 3/4" STRUCTURAL I plywood sheathing ranges from 1622 to 2241 plf, this test series is the first time that the plywood has been subjected to shear loads sufficient to cause panel shear failure.

Figure 14 shows the shear failure that occurred in Diaphragm 10. This failure emphasizes the necessity for checking the internal as well as boundary shear in high-load diaphragm design.

Correlation with Table 1 Values

The Table 1 value corresponding to this diaphragm fastener schedule is 1410 plf.

The test diaphragm design shear is less due to reduced nail penetration.

FIGURE 14

DIAPHRAGM 10 AFTER FAILURE.

DIAPHRAGMS WITH OPENINGS

Diaphragm No. 3

Purpose

This diaphragm was constructed with openings to test their effect on diaphragm strength.

Construction

The framing and panel layout of Diaphragm 3 was identical to No. 1 except for the addition of the 4-ft x 4-ft openings centered 8 ft from each end, with increased nailing adjacent to the openings. Figure 15 (page 20) shows details.

Design

Recommended Design Shear

The omission of sheathing, because of the openings, causes an increase in the shear in the remaining plywood. To resist the increased shear, the nail spacing was arbitrarily decreased from 6" o.c. to 3" o.c. along all edges of the partial panels of plywood adjacent to the opening.

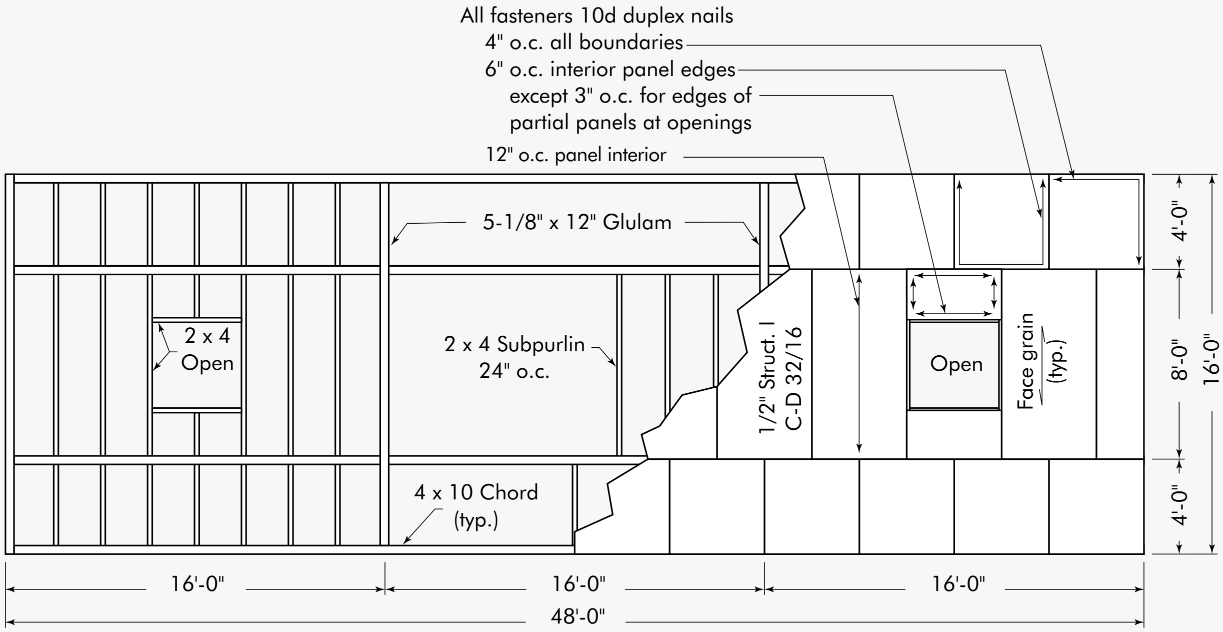
Recommended design shear = 435 plf, limited by fasteners at boundary (see Diaphragm 1).

Deflection

The deflection equation cannot be used to calculate deflection of diaphragms with openings.

FIGURE 15

FRAMING DETAILS AND PANEL LAYOUT FOR DIAPHRAGM 3.



Test Results and Discussion

Measured midpoint deflection on the second cycle (electronic problems prevented recording deflection on the first cycle) was 0.311" at the test load of 425 plf. This deflection is virtually the same as that of the identical diaphragm without openings. (See Diaphragm 1.)

The diaphragm failed at a boundary shear of 1314 plf, corresponding to a load factor of 3.02. Failure occurred when the compressive forces generated at the corners of the openings caused the plywood to buckle. No attempt had been made to modify or strengthen the boundary framing at the openings. The mode of failure made it obvious that there must be sufficient framing at an opening to redistribute the forces generated by the opening back into the diaphragm.

The forces generated by the opening may be calculated by applying the principles of statics. A design example showing a method of calculating chord forces and plywood shears around openings is given in Appendix E. However, when openings are relatively small, chord forces do not increase significantly and it is usually sufficient simply to reinforce perimeter framing and assure that it is continuous. Continuous framing should extend from each corner of the opening both directions into the diaphragm, a distance equal to the largest dimension of the opening.

Diaphragm No. 4

Purpose

This diaphragm, with 8-ft x 8-ft openings, was tested to determine the effect of larger openings on diaphragm performance.

Construction

The framing and panel layout of this diaphragm was identical to No. 1 except that 8-ft x 8-ft openings were centered 10 ft from each end. Also, the size of several framing members adjacent to the openings were increased. The framing size was increased primarily to provide sufficient width for the increased number of nails required in the high shear areas along the opening. Details of the framing and panel layout are shown in Figure 16.

Design

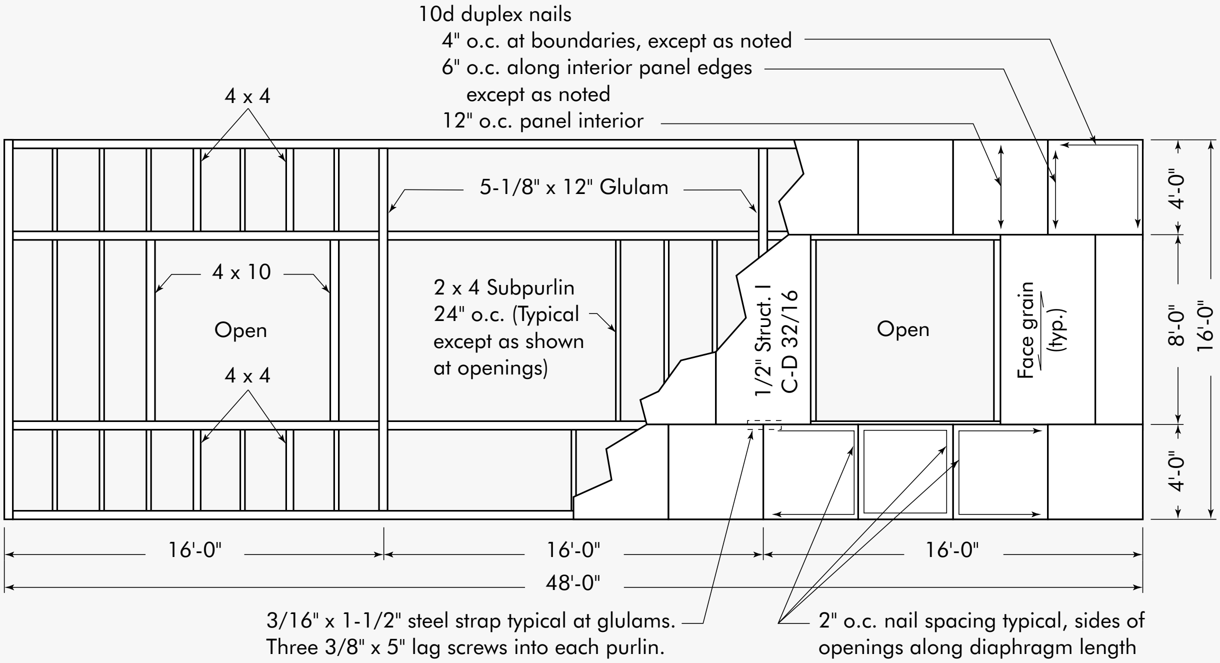
Recommended Design Shear

The 8-ft x 8-ft openings, very large relative to the size of the diaphragm, removed 50% of the plywood from the high shear areas near each reaction. The number of nails was, therefore, doubled along the panel edges of the plywood remaining along the openings.

Engineering theory can be used to calculate the tension and compression forces generated in the framing members around the openings. Since wind and seismic loads can come from any

FIGURE 16

FRAMING DETAILS AND PANEL LAYOUT FOR DIAPHRAGM 4.



direction, the calculations must consider the lateral force applied from each direction.

Recommended design shear = 435 plf, limited by fasteners at boundary (see Diaphragm 1).

Deflection
The deflection equation is not applicable to diaphragms with openings.

Test Results and Discussion
The midpoint deflection on the first test cycle, at a shear of 425 plf, was 0.506".

The diaphragm failed at a boundary shear of 1482 plf, corresponding to a load factor of 3.41. Failure occurred when the tensile force at one corner of an opening caused a framing member to pull from a purlin at the boundary of the opening. This failure is shown in Figure 17. The photo clearly shows the need for a tension connection at the corner. The only resistance to the tension force at this corner was a nailed plywood butt joint over the framing, and nails fastening the framing anchor, which are loaded in withdrawal.

Strain readings on the tension chords during the entire series of diaphragm tests indicate that the chord tension stress averages only 81% of its theoretical value at diaphragm design load or at double design load. (Theoretical chord stress is based on the assumption that the chords carry the entire bending component and the plywood carries the entire shear component of the load.)

FIGURE 17

FAILURE AREA OF DIAPHRAGM 4.

The strain readings made during the test of Diaphragm 4 with the 8-ft x 8-ft openings indicated that the measured tension stress in the chord exceeded the theoretical stress. The mathematical analysis made after the test (see Appendix E) showed that the increase in the chord stress above that predicted was directly attributable to the effect of the shear being transferred around the openings. This shear transfer resulted in increased tension and compression stresses in the framing on each side of the 4-ft widths of the diaphragm remaining along the openings. Since one of the framing members on each side was also the diaphragm chord, these stresses added to the stresses in the chord from the diaphragm as a whole.

FIELD-GLUED DIAPHRAGMS

Diaphragm No. 5

Purpose

This diaphragm was the first of two tested to determine the performance of diaphragms with plywood sheathing which has been field-glued to the lumber framing.

Construction

Diaphragm 5 was built with 1/2" APA STRUCTURAL I C-D 32/16 plywood sheathing, using the same panel layout and framing as Diaphragm 1 (see Figure 6 on page 8), but with an AFG-01 construction adhesive* to bond the plywood to the framing. Ten-penny common nails were driven 12" o.c. at all panel edges and in the panel interior over intermediate framing members to provide contact pressure for the adhesive. A single glue bead (approximately 1/4" in diameter) was applied to the 2" nominal framing member that supported an edge joint in the plywood. Also, two beads were applied to the 4" nominal lumber chord around the perimeter of the diaphragm.

Design

Recommended Design Shear

Traditionally, diaphragms have been engineered on the basis of the flanges taking all tension and compression forces and the plywood taking all of the shear. The failures in the two field-glued diaphragms indicate a stress distribution similar to that for a glued plywood-lumber beam, where there is complete composite action between the plywood web and the lumber flange. The box beam design method is used to determine the design shear. See PDS Supplement 2 *(13)* for a complete description of the design method. See Figure 18 for dimensions and details at the location which is critical for design purposes.

Allowable load based on adhesive shear stress

Allowable load, $V = v_g b_g I/bQ$

Where V = diaphragm shear at boundary (plf)

v_g = design glueline shear (psi)

b_g = width of glueline (in.)

I = moment of inertia or chords, purlins, and parallel-grain plies of the plywood ($in.^4$)

b = diaphragm width (ft)

Q = first moment of the chord, purlins, and plywood outside the critical glueline ($in.^3$)

v_g = 50 psi (This value corresponds to one-third the minimum average ultimate shear stress required for AFG-01 adhesives under typical application conditions. The value is selected to demonstrate the design method, but should not be construed as a recommended design shear due to significant variability in application conditions and workmanship, as well as in individual shear test results.)

b_g = 1 in. (assumed)

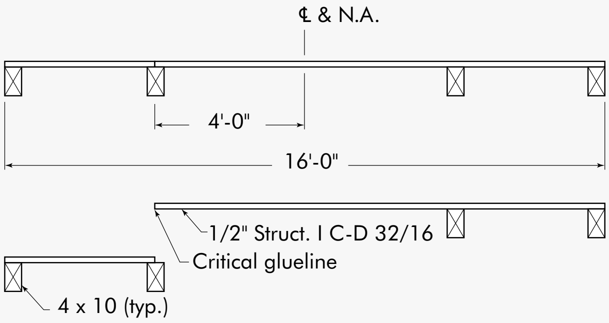
I = 838773 $in.^4$ (see *(13)* for design method, and Figure 18)

Q = 5275 $in.^3$ (see *(13)* for design method, and Figure 18)

Recommended design shear (at boundary) = 50(1)(838773)/16(5275) = 495 plf, limited by shear capacity of glueline at continuous interior panel joint.

FIGURE 18

CROSS SECTION OF DIAPHRAGM 5.



*Glue conforming to APA Performance Specification AFG-01 or ASTM specification D3498. These specifications require glues to develop adequate shear strength under a wide variation of moisture and temperature conditions, and to possess gap-filling capability, and durability in exposure to moisture and air.

Deflection

Assuming the glued diaphragm behaves as a glued box beam *(13)*, diaphragm deflection Δ =

$$\underbrace{\frac{45VbL^3}{EI}}_{\text{bending deflection (terms collected)}} + \underbrace{\frac{KC}{AG}}_{\text{shear deflection}} + \underbrace{\frac{\Sigma(\Delta_c X)}{2b}}_{\text{deflection due to chord splice slip}}$$

Where K = a factor determined by the beam (diaphragm) cross section from PDS Supplement 2 *(13)*

C = a coefficient determined by the manner of loading (in.-lb) from PDS Supplement 2 *(13)*

A = area of the beam (diaphragm) cross section (in.^{2})

Other terms as defined on pages 22 and 9.

For Diaphragm 5, deflection is calculated for a shear of 425 plf, since this was the test load used in the first two loading cycles, when deflection was measured.

Chord joint slip (estimated from test data):

Tension chord: 0.016" at 1/4 point; 0.022" at center
Compression chord: 0.002" at 1/4 point; 0.003" at center

K = 1.67 (see *(13)* for method; interior girders ignored for simplicity)

C = 978048 in.-lb (see *(13)* for method)

A = 169 in.^{2} (interior girders ignored)

$$\Delta = \frac{45\ (425)\ (16)\ (48^3)}{(1.7 \times 10^6 \times 1.03)\ (838773)} + \frac{1.67\ (978048)}{169\ (90000)}$$

$$+ \frac{(2 \times .016 \times 12) + (.022 \times 24) + (2 \times .002 \times 12) + (.003 \times 24)}{2(16)}$$

$$= 0.023 + 0.107 + 0.032 = 0.162 \text{ in.}$$

Test Results and Discussion

Diaphragm 5 proved to be considerably stronger and stiffer than expected. After reviewing the deflection from two cycles of testing to a load of 425 plf, the test load was increased to 700 plf for the remaining six cycles of the test. The measured midpoint deflections were 0.193" at a test load of 425 plf on the first loading cycle (within 1/32" of 0.162" calculated) and 0.327" at a test load of 700 plf on the third cycle.

Failure occurred at a boundary shear of 2359 plf when the compression component of the shear caused a plywood panel to buckle. This failure was along the continuous panel joint 4 ft from the tension chord. Failures caused by shear forces acting parallel to the length of the diaphragm are unusual, but the significance of this was not recognized until the test of Diaphragm 6 resulted in a similar failure.

The diaphragm design is based on shear along an interior glue line (where failure occurred) and the load factor is:

$$\text{Shear, } v_g b_g = \frac{VbQ}{I} = \frac{2359(16)(5275)}{838773} = 237 \text{ lb/in.}$$

$$\text{Load factor} = \frac{237}{50(1)} = 4.74$$

Diaphragm No. 6

Purpose

This diaphragm, the second of two field-glued specimens, was tested to determine the effect of gluing the plywood sheathing to truss framing.

Construction

Diaphragm 6 was fabricated with 5/8" APA STRUCTURAL I C-D 42/20* plywood sheathing, using an AFG-01 construction adhesive to bond the plywood to framing consisting of wood I-joists spaced 32" o.c. The adhesive application was identical to that used in Diaphragm 5, except the fasteners were 8d common nails spaced 12" o.c.

The panel layout and framing was identical to Diaphragm 7. See Figure 9 (page 13) for details.

*Span Rating now redesignated to 40/20.

Design

Recommended Design Shear

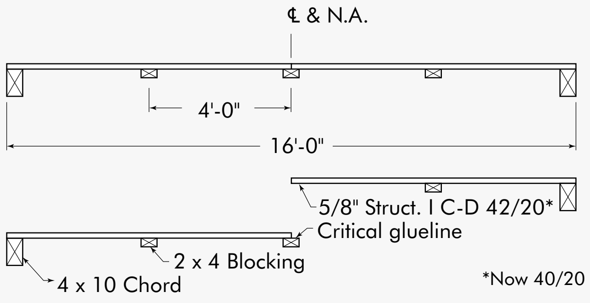
See Diaphragm 5 for a summary of the method of calculation. Figure 19 (page24) shows the cross section details of the diaphragm. In Diaphragm 5 the critical glueline is at the longitudinal centerline of the diaphragm. The 2x4 blocking is omitted from the calculations for I and Q since it is not continuous.

I = 745507 in.^{4}
Q = 4382 in.^{3}

Recommended design shear (at boundary) = 50(1)(745507)/ 16(4382) = 530 plf, limited by shear capacity of glueline at continuous interior panel joint.

FIGURE 19

CROSS SECTION OF DIAPHRAGM 6.



Deflection

For Diaphragm 6, deflection is calculated for a shear of 660 plf, since this shear corresponds to the deflection measurement closest to design load. Measured chord splice slip was insignificant.

$K = 1.53$

$C = 1520640$ in.-lb

$A = 202$ in.^{2}

$$\Delta = \frac{45\ (660)\ (16)\ (48^3)}{(1.7 \times 10^6 \times 1.03)\ (745507)} + \frac{1.53\ (1520640)}{202\ (90000)}$$

$$= 0.040 + 0.128 = 0.168 \text{ in.}$$

Test Results and Discussion

A midpoint deflection of 0.857" was measured at a test load of 1320 plf on the first cycle of loading. Note that this test load was almost 2.5 times the recommended design load. The deflection at 660 plf, the test load increment that was the closest to the recommended design shear of 530 plf, was only 0.384", within 1/4" of the 0.168" calculated deflection.

Diaphragm 6, fastened with construction adhesive, failed at a boundary shear load of 2624 plf. The most significant point in this failure was that it occurred along the continuous plywood panel joint at mid-width of the diaphragm. Diaphragm failures are quite uncommon at this location. Mathematical analysis of the diaphragm using the design method for glued plywood beams indicates that the glued diaphragm acts as a large glued beam, with the highest shear at the neutral axis, or mid-width of the diaphragm.

The ratio of ultimate shear to the recommended design shear, or load factor, was 4.95, calculated as for Diaphragm 5.

DIAPHRAGM WITH FRAMING SPACED 5 FT O.C.

Diaphragm No. 11

Purpose

This diaphragm was tested to determine the diaphragm performance of 4-ft x 10-ft, 7/8"-thick APA C-D plywood sheathing panels* when placed over supports spaced 5 ft o.c. The test included evaluation of a stapled T&G joint in lieu of blocking.

*Now designated APA Rated Sheathing 60/32, Exposure 1.

Construction

This diaphragm used 7/8"-thick APA C-D plywood (4-ft x 10-ft panels) with a T&G joint cut into the long panel edges. The plywood was applied to conventional framing using 4x10 joists. To accommodate the 5-ft joist spacing increments, the diaphragm length was increased to 50 ft. See Figure 20 for construction details.

Diaphragm 11 was the only diaphragm in the entire test series that was not constructed using STRUCTURAL I plywood. The 10-ft panels were manufactured with Species Group 1 face and back and Group 4 center and cores. This combination is representative of the weakest combination of species that will provide adequate strength and stiffness to resist normal design roof live and dead load (for construction with joists spaced 5 ft o.c.). The plywood was attached to the framing with 14-ga x 2-3/8"-long staples. The staple length was chosen to obtain penetration equivalent to the maximum possible if the plywood was fastened to a flat 2x4 nailer on a steel truss, or to a flat chord truss manufactured with 2x lumber.

The long plywood panel edges perpendicular to the framing were not blocked. The T&G edge transfers vertical load between adjacent panels. Staples were driven through the T&G joint to transfer shear. These staples were 16-ga x 1" long and were spaced 1" o.c., with the crowns parallel to the T&G joint.

Design

Recommended Design Shear

Allowable load based on plywood shear stress, V_{cp}

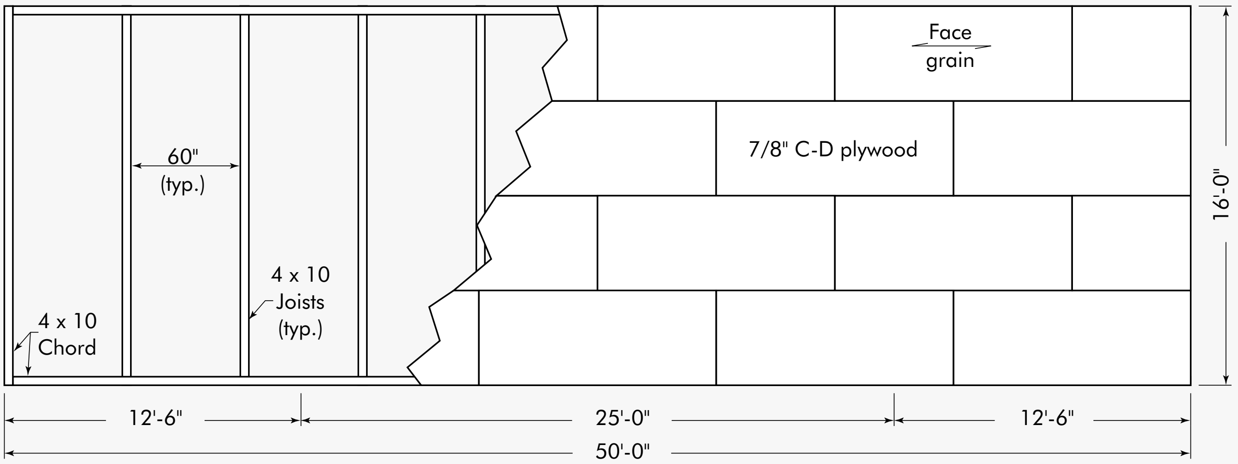
$$V_{cp} = 190 \times 1.33 \times 12 \times \underbrace{0.607}_{\text{effective thickness for shear for 7/8" C-D plywood (8)}} = 1841 \text{ plf}$$

Allowable load based on lateral fastener load at boundary, V_{np}

No reduction is necessary for using C-D plywood, since its thickness is 1/8" or more greater than the 5/8" minimum for use with 14-ga staples.

FIGURE 20

FRAMING DETAILS AND PLYWOOD PANEL LAYOUT FOR DIAPHRAGM 11.



Fasteners for center 1/2
- 14-ga x 2-3/8" staples
  - 3" o.c. along boundary
  - 4" o.c. at 4' interior panel ends
  - 6" o.c. in panel interior
- 16-ga x 1" staples
  - 2" o.c. at T&G edges

Fasteners for end 1/4
- 14-ga x 2-3/8" staples
  - 2 rows 3" o.c. along boundary
  - 2" o.c. at 4' interior panel ends
  - 6" o.c. in panel interior
- 16-ga x 1" staples
  - 1" o.c. at T&G edges

$$V_{np} = 75 \times 1.33 \times 8 \times (\underbrace{1.5}_{\text{fastener penetration into framing}}/4 + 0.50) = 698 \text{ plf}$$

Allowable load based on lateral fastener load at T&G joint, V_{nj}

$$V_{nj} = \underbrace{52}_{\text{design lateral load for 16-ga staples } (12)} \times 1.33 \times 12 \times \underbrace{0.90}_{\text{reduction for C-D plywood } (3)} = 747 \text{ plf}$$

Recommended design shear = 700 plf (rounded to the nearest 5 plf), limited by fasteners at boundary.

Deflection

The diaphragm deflection equation is not applicable when multiple sizes of fasteners are used.

Test Results and Discussion

The midpoint deflection on the first test cycle was 0.345" at a test load of 600 plf. At 800 plf, the maximum shear on the first cycle, the deflection was 0.492".

Failure occurred at a boundary shear of 2375 plf when the staple crowns along 5 ft of stapled T&G joint pulled through the plywood. This was immediately followed by plywood shearing from the end chord.

The controlling diaphragm shear capacity is based on the fasteners at the boundary, and the corresponding load factor is 3.39.

The stiffness of the stapled T&G joint exceeded the stiffness of normal blocking. This high degree of stiffness is indicated by comparing the panel slip measured along the T&G joint with that measured at a plywood butt joint over framing. At 800 plf shear, the slip at the T&G joint was 0.012" (average of measurements at six locations) while the slip at the butt joint was 0.030" (average of two locations).

SUMMARY

Construction details of the diaphragms are summarized in Table 2. Table 3 summarizes the test results (see pages 27-28).

CONCLUSIONS

The following conclusions are based on analysis of the testing described in this report. They are consistent with previously reported diaphragm tests *(1, 2, 3, 10, 11)*.

1. Engineering theory, using commonly accepted values for lateral fastener loads and plywood shear capacity, can be used to mathematically compute diaphragm shears higher than those previously published.

A. The most useful methods of obtaining higher diaphragm shears are:

a. Increasing the number of fasteners per foot. Often this will require multiple rows of fasteners to prevent lumber from splitting.

b. Adding a second layer of plywood in the areas of high shear.

B. Highly loaded diaphragms must include a check of the shear capacity of the plywood.

2. Pneumatically driven staples are suitable fasteners for diaphragms. They can be closely spaced without damage to plywood or framing.

3. Diaphragms can be field glued using construction adhesives and a reduced number of fasteners (spaced 12" o.c. or less). The design is based on the shear strength of construction adhesives, which will generally limit the diaphragm design shear to values which can be obtained by use of nails or staples. Analysis of glued plywood diaphragms should be based on glued plywood beam design methods.

4. The weakening effect of openings in diaphragms can be offset by designing for the increased shear around the openings due to the reduced plywood web area, and for the tension and compression forces at each corner of the opening and at chords.

TABLE 2

CONSTRUCTION DETAILS

Test No.	Plywood[7]	Fasteners					Framing	Special Features
				Schedule[2]				
		Size	Spacing[1] (in.)	End 8' (1/6 length) (High Shear)	Next 8' (1/6 length) (Medium Shear)	Center 16' (1/3 length) (Low Shear)		
1	1/2" STRUC. I C-C 32/16 EXT	10d common[3]	4, 6, & 12	Uniform fastener spacing throughout.			2x4 24" o.c.	–
2	1/2" STRUC. I C-D 32/16	10d common[3] 14-ga x 1-3/4"[4]	4, 6, & 12 3, & 12[9]	Bottom layer, uniform spacing throughout. Top layer, B. Nails 4" o.c. E. staples 3" o.c. I. staples 12" o.c. grid			2x4 24" o.c.	2 layers
3	1/2" STRUC. I C-C 32/16	10d common[3]	4, 6, & 12	Uniform spacing, except 3" o.c. at all edges of partial panels at openings.			2x4 24" o.c.	4-ft x 4-ft openings
4	1/2" STRUC. I C-D 32/16	10d common[3]	4, 6, & 12	Uniform spacing, except 2" o.c. at edges of 4-ft x 4-ft plywood panels adjacent to openings.			2x4[5] 24" o.c.	8-ft x 8-ft openings
5	1/2" STRUC. I C-D 32/16	10d common[3]	12, 12, & 12	Uniform fastener spacing throughout.			2x4 24" o.c.	Field-glued
6	5/8" STRUC. I C-D 42/20[6]	8d common[3]	12, 12, & 12	Uniform fastener spacing throughout.			Wood I-Joist 32" o.c.	Field-glued
7	5/8" STRUC. I C-D 42/20[6]	14-ga x 1-3/4"[4]	2/3, 1, & 6	B. 3 rows at 2" o.c. E. 1 row at 1" o.c. I. 1 row at 6" o.c.	2 rows at 2" o.c. 1 row at 1.5" o.c. 1 row at 8" o.c.	1 row at 2" o.c. 1 row at 3" o.c. 1 row at 12" o.c.	Wood I-Joist 32" o.c.	–
8	3/4" STRUC. I C-D 48/24	14-ga x 2-3/4"[4] 14-ga x 3"	1/2, 3/4, & 3	B. 3 rows at 1.5" o.c. E. 2 rows at 1.5" o.c. I. 1 row at 3" o.c.	3 rows at 2.25" o.c. 2 rows at 2.25" o.c. 1 row at 4" o.c.	2 rows at 3" o.c. 1 row at 2.25" o.c. 1 row at 6" o.c.	4x10 48" o.c.	–
9	3/4" STRUC. I C-D 48/24	10d "short" 0.148" dia. x 2-1/4"	1, 1-1/2, & 6	B. 3 rows at 3" o.c. E. 2 rows at 3" o.c. 1. 1 row at 6" o.c.	3 rows at 4" o.c. 2 rows at 4" o.c. 1 row at 6" o.c.	1 row at 3" o.c. 1 row at 4" o.c. 1 row at 6" o.c.	4x10 48" o.c.	–
10	3/4" STRUC. I C-D 48/24	10d "short" 0.148" dia. x 2-1/4"	1, 1-1/2, & 6	B. 3 rows at 3" o.c. E. 2 rows at 3" o.c. I. 1 row at 6" o.c.	3 rows at 4" o.c. 2 rows at 4" o.c. 1 row at 6" o.c.	1 row at 3" o.c. 1 row at 4" o.c. 1 row at 6" o.c.	4x10 48" o.c.	–
11	7/8" Group 1 C-D[8]	14-ga x 2-3/8" 16-ga x 1"	1-1/2, 2, & 6 1 @ T&G	Ply. to lbr., B. 2 rows at 3" o.c. E. 1 row at 2" o.c. I. 1 row at 6" o.c. T&G, 1 row at 1" o.c.		1 row at 3" o.c. 1 row at 4" o.c. 1 row at 6" o.c. 1 row at 2" o.c.	4x10 60" o.c.	10' plywood

(1) The first number is the fasteners along the diaphragm perimeter (chords); the second, panel edges (except at chords); the third, panel interior to intermediate joists.

(2) B = diaphragm Boundary, E = interior panel Edges, I = panel interior to Intermediate framing members.

(3) Duplex head nails were used wherever possible, to facilitate disassembly. Net length is 2-3/4" for 10d and 2-1/4" for 8d.

(4) These staples were polymer coated.

(5) 4x4 substituted where shown in Figure 16, fastened with nails 2" o.c.

(6) Span Rating now redesignated to 40/20.

(7) APA Structural I Rated Sheathing, Exposure 1 (except as noted).

(8) Now designated APA Rated Sheathing 60/32, Exposure 1.

(9) Top layer – 10d common nails 4" o.c. at boundary.

TABLE 3

SUMMARY OF TEST RESULTS

		Fasteners				Deflection						
Test No.	Plywood(6)	Size	Spacing at End Chord (in.)	Framing	Special Features	Calc. (in.)	Meas. (in.)	At Shear (plf)	Failure	Ult. Shear (plf)	Design Shear (plf)	Load Factor
1	1/2" STRUC. I C-C 32/16 EXT	10d common(3)	4	2x4 24" o.c.	–	0.294	0.312	425	Fastener pull-through and panel edge crushing	1788+(4)	435	4.11+
2	1/2" STRUC. I C-C 32/16	10d common(3) 14-ga x 1-3/4"(1)	4/2	2x4 24" o.c.	2 layers	–	0.421	850	Fastener pull-through and withdrawal at boundary	3456	870	3.97
3	1/2" STRUC. I C-C 32/16	10d common(3)	4	2x4 24" o.c.	4-ft x 4-ft openings	–	0.311	425	Plywood buckled at openings	1314	435	3.02
4	1/2" STRUC. I C-D 32/16	10d common(3)	4	2x4 24" o.c.	8-ft x 8-ft openings	–	0.506	425	Framing joint at corner of opening	1482	435	3.41
5	1/2" STRUC. I C-D 32/16	10d common(3)	–	2x4 24" o.c.	Field-glued	0.162	0.193	425	Glueline at interior longitudinal joint	2359	495	4.74
6	5/8" STRUC.I C-D 42/20(5)	8d common(3)	–	Wood I-Joist 32" o.c.	Field-glued	0.168	0.384	660	Glueline at interior longitudinal joint	2624	530	4.95
7	5/8" STRUC. I C-D 42/20(5)	14-ga x 1-3/4"(1)	2/3	Wood I-Joist 32" o.c.	–	1.020	0.588	1325	Fastener withdrawal	3925	1345	2.92
8	3/4" STRUC. I C-D 48/24	14-ga x 2-3/4"(1) 14-ga x 3"	1/2	4x10 48" o.c.	–	0.860	0.770	1760	Hold-down (test setup)	5234+(2)	1840	2.85+
9	3/4" STRUC. I C-D 48/24	10d "short" 0.148" dia x 2-1/4	1	4x10 48" o.c.	–	1.017	1.192	1800	Compression buckling of lumber chord	4668+(2)	1280	3.65+
10	3/4" STRUC. I C-D 48/24	10d "short" 0.148" dia x 2-1/4"	1	4x10 48" o.c.	–	0.896	1.108	1800	Shear through the plywood	4946	1280	3.86
11	7/8" Group 1 C-D(7)	14-ga x 2-3/8" 16-ga x 1"	1-1/2 1 @ T&G	4x10 60" o.c.	10' plywood	–	0.345	600	Fastener pull-through at T&G joint	2375	700	3.39

(1) These staples were polymer coated.

(2) The failure was in a connection between framing and test setup. Ultimate load was not reached for plywood or fasteners.

(3) Duplex head nails were used wherever possible, to facilitate disassembly. Net length is 2-3/4" for 10d and 2-1/4" for 8d.

(4) Test was stopped before actual failure when some cylinders reached maximum extension.

(5) Span Rating now redesignated to 40/20.

(6) APA Structural I Rated Sheathing, Exposure 1 (except as noted).

(7) Now designated APA Rated Sheathing 60/32, Exposure 1.

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NOTE: In 1964, the Douglas Fir Plywood Association was renamed the American Plywood Association. In 1994, the name was changed to *APA – The Engineered Wood Association.*

APPENDIX A

Summary of Previous Diaphragm Tests

Recommended Shears for Plywood Diaphragms

Design shears in Table A-1 were developed based on test results summarized in this Appendix and are recognized in the major model building codes. Tabulated shears are for wind or seismic loading. Reduce values 25 percent for “normal” load duration.

Diaphragm Test Results

Tables A-3, A-4 and A-5 (pages 32-34) summarize construction details and results of previous full-scale diaphragm tests conducted by *APA – The Engineered Wood Association (1, 2, 3)*. Plywood descriptions have been updated to reflect grade terminology of U.S. Product Standard PS 1 (16).

Diaphragm Design Factors

Previous tests established the following factors to be used in the design of plywood diaphragms. Except as noted, research discussed in the body of this report did not suggest revision of these factors. The factors for panel edges in blocked diaphragms are summarized in Table A-2 (page 32).

1. Plywood containing Species Group 2, 3 or 4 veneer.

a. Diaphragm design shears are 90 percent of those for all-Group-1 panels of the same thickness, for the same nail size and spacing *(3)*.

b. Diaphragm design shears are 100 percent of those for STRUCTURAL I (all-Group-1) panels one size thinner, for the same nail size and spacing, if minimum nail penetration into framing is maintained *(3)*.

2. Design shears must be reduced 11 percent when 2-in.-nominal lumber is used *(1)*. (This reduction also applies to 2 rows of fasteners in 3-in.-nominal lumber, and 3 rows of fasteners in 4-in.-nominal lumber.)

3. The following reductions must be applied for close nail spacing. These are in addition to the 11 percent for 2-in. framing, if also applicable.

a. Fifteen percent for nail spacing 2" on center at the boundary.

b. Ten percent for 10d nails 2" or 2-1/2" on center at the boundary when boundary members are single 2-in.-wide members. This reduction is in addition to 3a for 2" nail spacing. (It has been subsequently specified that framing at adjoining panel edges shall be 3-in. nominal or wider, and nails shall be staggered where nails are spaced 2" or 2-1/2" o.c., and where 10d nails having penetration into framing of more than 1-5/8" are spaced 3" o.c.)

4. Nailing 4" o.c. at the boundary and 6" o.c. at interior panel edges is used as the “basic” shear to derive the following values for lightly loaded diaphragms:

a. Blocked with 6" o.c. boundary and 6" o.c. panel-edge nailing, use 75 percent.

b. Unblocked (See Table A-1 for illustration of “cases”):

(1) Case 1, use 67 percent.

(2) Case 2 through 6, use 50 percent.

Caution: The following nails fully develop the strength potential of plywood listed. Using larger nails will not result in a higher allowable design load. Example: 10d nails could be used for fastening 3/8" STRUCTURAL I plywood, but the design shear should be based on 8d nail values.

Nail	STRUCTURAL I Plywood	Other Plywood
6d common	1/4"or 5/16"	3/8"
8d common	3/8"	15/32"
10d common	15/32"	19/32"

TABLE A-1

RECOMMENDED SHEAR IN POUNDS PER FOOT FOR HORIZONTAL PLYWOOD DIAPHRAGMS WITH FRAMING OF DOUGLAS FIR, LARCH OR SOUTHERN PINE[a] FOR WIND OR SEISMIC LOADING

Plywood Grade[d]	Common Nail Size	Minimum Nail Penetration in Framing (inches)	Minimum Plywood Thickness (inch)	Minimum Nominal Width of Framing Member (inches)	Blocked Diaphragms				Unblocked Diaphragms	
					Nail Spacing (in.) at diaphragm boundaries (all cases), at continuous panel edges parallel to load (Cases 3 & 4), and at all panel edges (Cases 5 & 6)[b]				Nails Spaced 6" max. at supported edges[b]	
					6	4	2-1/2[c]	2[c]	Case 1 (no unblocked edges or continuous joints parallel to load)	All other configurations (Cases 2, 3, 4, 5 & 6)
					Nail Spacing (in.) at other panel edges (Cases 1, 2, 3 & 4)					
					6	6	4	3		
STRUCTURAL I	6d	1-1/4	5/16	2	185	250	375	420	165	125
				3	210	280	420	475	185	140
	8d	1-1/2	3/8	2	270	360	530	600	240	180
				3	300	400	600	675	265	200
	10d	1-5/8	15/32	2	320	425	640	730[c]	285	215
				3	360	480	720	820	320	240
C-D C-C and other APA grades except Species Group 5	6d	1-1/4	5/16	2	170	225	335	380	150	110
				3	190	250	380	430	170	125
			3/8	2	185	250	375	420	165	125
				3	210	280	420	475	185	140
	8d	1-1/2	3/8	2	240	320	480	545	215	160
				3	270	360	540	610	240	180
			15/32	2	270	360	530	600	240	180
				3	300	400	600	675	265	200
	10d	1-5/8	15/32	2	290	385	575	655[c]	255	190
				3	325	430	650	735	290	215
			19/32	2	320	425	640	730[c]	285	215
				3	360	480	720	820	320	240

(a) For framing of other species: (1) Find species group of lumber in AF&PA National Design Specification. (2) Find shear value from table for nail size, and for Structural I plywood (regardless of actual grade). (3) Multiply value by 0.82 for species with specific gravity of 0.42 to 0.49, and 0.65 for species with a specific gravity of less than 0.42.

(b) Space nails 12 in. o.c. along intermediate framing members.

(c) Framing shall be 3-in. nominal or wider, and nails shall be staggered where nails are spaced 2 in. or 2-1/2 in. o.c., and where 10d nails having penetration into framing of more than 1-5/8 in. are spaced 3 in. o.c. Exception: Unless otherwise required, 2-in. nominal framing may be used where full nailing surface width is available and nails are staggered.

(d) Current nomenclature for APA trademarked C-D and C-C panels is APA Rated Sheathing. C-D panels typically are classified Exposure 1 and C-C panels are classified Exterior. Structural I panels are so marked. See *APA Design/Construction Guide – Residential & Commercial* for recommended shear values for APA performance-rated wood structural panels.

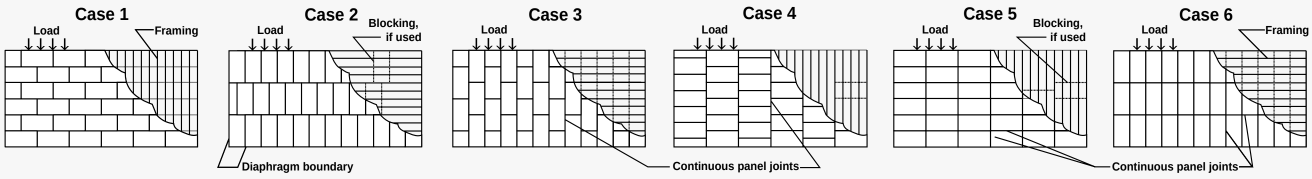


TABLE A-2

SUMMARY OF DESIGN REDUCTION FACTORS FOR NAILS IN STRUCTURAL I(a) BLOCKED PLYWOOD DIAPHRAGMS

Common Nail Size	Lines of Nails	Minimum Nominal Width of Framing Member (in.)	Nail Spacing Per Line at Panel Edges (in.)		
			2	2-1/2	3 or more
6d & 8d	1	2	.89 x .85	.89	.89
		3	.85	1.0	1.0
	2	3	.89 x .85	.89	.89
		4	.85	1.0	1.0
	3	4	.89 x .85	.89	.89
10d	1	2	.89 x .85 x .90(b)	.89 x .90(b)	.89
		3	.85	1.0	1.0
	2	3	.89 x .85 x .90	.89 x .90	.89
		4	.85	1.0	1.0
	3	4	.89 x .85 x .90	.89 x .90	.89

(a) Apply an additional factor of .90 for plywood other than STRUCTURAL I, or increase plywood thickness one size.

(b) 2 in. nominal width framing is not allowed with closely spaced 10d nails along interior panel joints. See 3b on page 29.

TABLE A-3

SUMMARY OF 1952 DIAPHRAGM TESTS(1)

Test No.	Figure(1)	Framing	Plywood(4)	Nailing(2)	Shear		Load Factor
					Ultimate	Design	
I	1-A	2x10 24" o.c. Blocked	1/2" STRUCT. I C-D 32/16	8d common 3, 6, 12	1380	360	3.83
II	1-A	2x10 24" o.c. Blocked	1/2" STRUCT. I C-D 32/16	10d common 2(3), 4, 12	1920	640	3.00
III	1-B	2x10 24" o.c. Blocked	1/2" STRUCT. I C-D 32/16	8d common 3, 6, 12	1756	360	4.88
IV	1-B	2x10 24" o.c. Unblocked	1/2" STRUCT. I C-D 32/16	8d common 6, 6, 12	1400	240	5.83

(1) See Figure A-1 (page 34) for layouts and dimensions of the test specimens.

(2) Following nail size, the first number is fastener spacing along the entire diaphragm boundary; second, interior panel edges; and third, panel interior nailing to intermediate joists.

(3) End chord was a double 2x10. Nailing was 4" o.c. into each.

(4) APA Structural I Rated Sheathing, Exposure 1.

TABLE A-4

SUMMARY OF 1954 DIAPHRAGM TESTS *(2)*

Test No.	Figure(1)	Framing	Plywood(6)	Nailing(2)	Shear		Load Factor
					Ultimate	Design	
A	1-C	2x12 24" o.c. Blocked	3/8" STRUCT. I C-D 24/0	8d common 4(3), 6, 12	1392	360	3.87
B	3-A	2x12 24" o.c. Blocked	3/8" STRUCT. I C-D 24/0	8d common 4(3), 6, 12	1490	360	4.14
C	1-C	2x12 24" o.c. Blocked	3/8" STRUCT. I C-D 24/0	8d common 4(3), 6, 12	1489	360	4.14
D	1-C	2x12 24" o.c. Unblocked	3/8" STRUCT. I C-D 24/0	8d common 6, 6, 12	1042	240	4.34
E	3-A	2x12 24" o.c. Unblocked	3/8" STRUCT. I C-D 24/0	8d common 6, 6,12	733	180	4.07
F	1-C	2x12 24" o.c. Unblocked	3/8" STRUCT. I C-D 24/0	8d common 3, 3, 12	1242	240	5.18
G	3-A	2x12 24" o.c. Unblocked	3/8" STRUCT. I C-D 24/0	8d common 3, 3, 12	806	180	4.48
H	4-A	2x12 24" o.c. Unblocked	3/8" STRUCT. I C-D 24/0	8d common 6, 6, 12	822	180	4.57
J	2-A	2x12 24" o.c. Unblocked	3/8" STRUCT. I C-D 24/0	8d common 6, 6, 12	814	180	4.52
K	1-C	2x12 16" o.c. Blocked	5/16" STRUCT. I C-D 20/0	6d common 2(3), 3, 12	2047	420	4.87
L	3-B	3x12 32" o.c. Blocked	1/2" STRUCT. I C-D 32/16	10d common 2-1/2(3), 4(4), 12	2264	720	3.14
M	1-C	3x12 48" o.c. Blocked	3/4" STRUCT. I C-D 48/24	10d common 2-1/2(3), 4,12	2530	720	3.51
N	1-C	3x12 48" o.c. Unblocked	3/4" STRUCT. I C-D 48/24	10d common 6, 6, 6	1260	320	3.94
O	1-C	2x12 24" o.c. Blocked	1/2" STRUCT. I C-D 32/16	8d common 4(3), 6, 12	1778	360	4.94
P	3-A	2x12 24" o.c. Blocked(5)	3/8" STRUCT. I C-D 24/0	8d common 4(3), 6, 12	1060	360	2.94

(1) See Figure A-1 (page 34) for layout and dimensions of the test specimens.

(2) Following nail size, except as modified by notes 3 and 4, the first number is fastener spacing along the entire diaphragm boundary; second, interior panel edges; and third, panel interior nailing to intermediate joists.

(3) This spacing was used only on boundaries parallel to load. The interior edge nail spacing was used on boundaries perpendicular to load.

(4) Nailing was increased, as required by the shears, on continuous panel joints parallel to load.

(5) Blocking was plywood cleats fastened with No. 8 screws.

(6) APA Structural I Rated Sheathing, Exposure 1.

TABLE A-5

SUMMARY OF 1966 DIAPHRAGM TESTS *(3)*

Test No.	Figure(1)	Framing	Plywood	Nailing(2)	Shear		Load Factor
					Ultimate	Design	
1	1-D	2x8 24" o.c. Blocked	3/8" STRUCT. I(7) C-D 24/0	8d common 4, 6, 12	1350	360	3.75
2	1-D	2x8 24" o.c. Blocked	3/8" STRUCT. I(7) C-D 24/0	8d common short(3) 4, 6, 12	1155	360	3.21
3	1-D	2x8 24" o.c. Blocked	3/8" STRUCT. I(7) C-D 24/0	8d common short(3) 4, 6, 12	1120	360	3.11
4	1-D	2x8 24" o.c. Blocked	3/8" STRUCT. I(7) C-D 24/0	8d common 4, 6, 12	1160	360	3.22
5	1-D	2x8 24" o.c. Blocked	3/8" C-D 24/0(8)	8d common 4, 6, 12	1115	320	3.48
6	1-D	2x8 24" o.c. Blocked	3/8" C-D 24/0(8)	8d common 2, 3, 12	1660	545	3.05
7	1-D	2x8 24" o.c. Blocked	3/8" C-D 24/0(8)	8d common 4, 6, 12	1120	320	3.50
8	1-D	2x8 24" o.c. Blocked	3/8" C-D 24/0(8)	8d common 4, 6, 12	1125	320	3.52
9	1-D	2x8 24" o.c. Blocked	1/2" C-D 24/0(8)	8d common 4, 6, 12	1380	360	3.83
10	1-D	2x8 24" o.c. Blocked	1/2" C-D 24/0(8)	10d common 4, 6, 12	1435	385	3.73
11	1-D	2x8 24" o.c. Blocked	1/2" C-D 24/0(8)	10d common 2, 3, 12	1860	590	3.15
12	1-D	Double 2x8 48" o.c. Unblocked	1-1/8" Under- layment T&G(9)	8d common ring shank 6, 6, 6	1135	320	3.55
12A	1-D	Double 2x8 48" o.c. Unblocked	1-1/8" Under- layment T&G(9)	8d common ring shank 6, 6, 6	1220	320	3.81
13	1-D	Double 2x8 48" o.c. Blocked(4)	1-1/8" Under- layment T&G(9)	8d common ring shank 4, 6, 6	2050	480	4.27
14	1-D	Double 2x8 48" o.c. Blocked(5)	1-1/8" Under- layment T&G(9)	10d common 2, 3, 6	2910	820	3.55
15	3-C	2x4 24" o.c. Blocked	3/8" STRUCT. I(7) C-D 24/0	8d common 4, 6(6), 12	1728	360	4.80
16	1-D	Steel trusses 4' o.c. Blocked	3/4" STRUCT. I(7) C-D 48/24	8d common 2-1/2, 4, 12	2960	600	4.93
17	2-B	Steel trusses 4' o.c. Unblocked	3/4" STRUCT. I(7) C-D 48/24	#10 Screw 16, 16, 16	600	190	3.16
18	2-B	Steel trusses 4' o.c. Unblocked	3/4" STRUCT. I(7) C-D 48/24	#10 Screw 6-1/2, 6-1/2, 16	720	190	3.79

(1) See Figure A-1 (page 34) for layout and dimensions of the test specimens.

(2) Following nail size, except as modified by note 6, the first number is fastener spacing along the entire diaphragm boundary; secondary interior panel edges; and third, panel interior nailing to intermediate joists.

(3) Nails were 1-7/8" long with a 0.131" shank diameter.

(4) “Blocked” construction was obtained by driving 16-ga staples through the T&G joint. Staples were 2" o.c. for end 1/4 of diaphragm and 4" o.c. in center 1/2.

(5) Same as (4) except staples were 1" o.c. for end 1/6, 1-3/4" o.c. for next 1/6 and 4" o.c. for center 1/3.

(6) Nailing was increased, as required by the shears, on continuous panel joints parallel to loads.

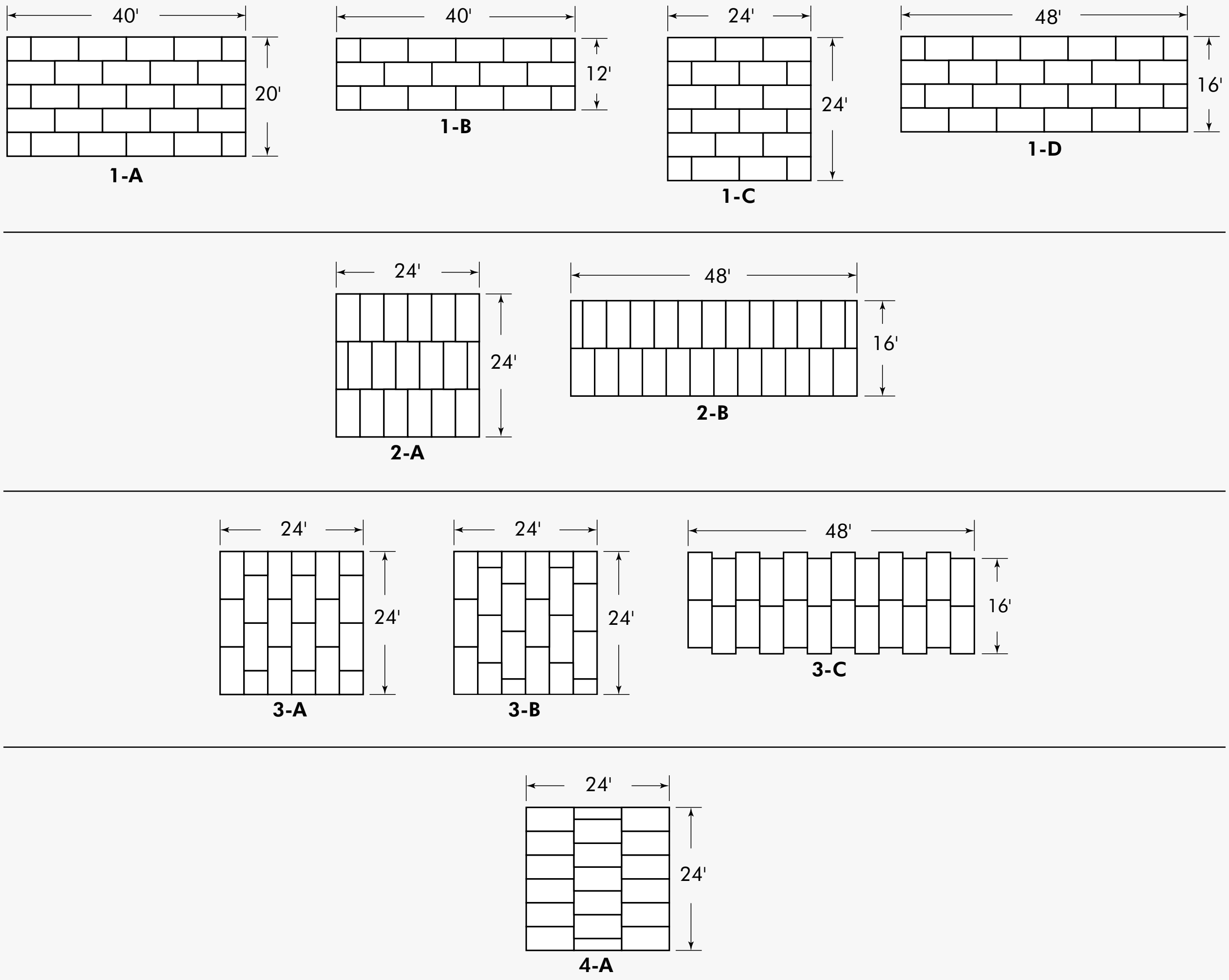
(7) APA Structural I Rated Sheathing, Exposure 1.

(8) APA Rated Sheathing, Exposure 1.

(9) APA Rated Sturd-I-Floor 48oc, Exposure 1 (formerly designated 2-4-1); tongue and groove edges.

FIGURE A-1

LAYOUT AND DIMENSIONS OF TEST SPECIMENS



APPENDIX B
SUPPLEMENTAL FASTENER TESTS

Part 1. Plywood Stapled to Lumber or Plywood

Purpose

Tests were conducted to develop information on lateral load capacity and load-slip characteristics of staples for this series of horizontal diaphragm tests.

Materials and Specimens

Plywood was manufactured with all plies of Group 1 species, and the lumber was Douglas-fir. 14-gage staples used to fabricate the specimens were obtained from two manufacturers. In some cases it was necessary to use solvent to remove plastic coating from the staples to evaluate performance of "bright staples." Also, in several instances the staples were cut to obtain the specific length required for the test.

In all specimens, the face grain of the plywood was oriented parallel to the load. The staples were driven with the crown parallel to plywood face grain. In the specimen using plywood for the substrate, the face grain of both layers of plywood was parallel to load. Staples were driven with an edge distance of 1" and end distance of 1-1/2".

Test Setup and Procedure

Details of the test setup are shown in Figure B-1.

Specimens were tested using the method outlined in ASTM D1761 *(15)*. This test method specifies a load application rate of 0.1 inches per minute and requires testing the specimens within one hour of fabrication. Joint deformation and ultimate load were recorded.

The testing deviated from one requirement of the ASTM method. The standard practice specifies that collated staples shall not be cleaned. The solvent used to remove plastic coating from some staples also cleaned the staples and removed the collating adhesive.

To minimize the effect of variability on the test, each of the 2x4 lumber members used for the test combining staple penetration and 1/2" plywood had the first piece of plywood attached with a 1-1/2" staple, the second with a 2" staple, and the third with a 2-3/4" staple. Similarly, in the plywood-to-plywood test, one piece of 3/8", one of 1/2", and one of 5/8" plywood was attached to each of the pieces of plywood tested for each thickness of substrate.

The test load was applied parallel to the grain in the lumber member and to the face grain of the plywood in all tests. The staple crown was also placed parallel to load.

FIGURE B-1

TYPICAL LOAD TEST SPECIMEN.
The load is applied to the lowest of three plywood pieces stapled to a 2x4 lumber framing member.

Test Results and Discussion

The results of the tests are summarized in the following tables.

The lateral load tests were conducted on both coated and bright staples, but only the results of the bright are shown. Recommended lateral loads for staples in this report are based on the tests of bright staples only. Test results of the polymer-coated staples were omitted for several reasons. First, the coatings vary among the manufacturers; second, all of the coatings tested improved the staple performance. Since the coating tended to increase the staple's load capacity, recommendations based on bright staples are conservative for both bright and polymer-coated staples. The recommendations do not apply to cement-coated staples, since tests at the Forest Products Laboratory and Purdue University indicate that cement coatings generally reduce the long-term load capability of the fastener.

The results of tests where plywood was stapled to plywood (Table B-2, page 38) indicate that an adequate load factor for the published design load of 75 lb per staple *(12)* can be obtained with a minimum 1/2" top layer and 5/8" substrate. For thinner plywood in either or both layers, an adequate load factor is maintained when design load is reduced in proportion to

TABLE B-1

PLYWOOD-STAPLE COMBINATIONS TESTED

PLYWOOD TO PLYWOOD 14-ga x 1-3/4"-long bright staples

	Number of Tests		
	Top Layer of Plywood		
Plywood Substrate	**3/8"**	**1/2"**	**5/8"**
1/2"	6	6	6
5/8"	6	6	6
3/4"	6	6	6

PLYWOOD TO LUMBER 14-ga bright staples, length as shown

	Number of Tests		
	Top Layer of Plywood		
Staple Length	**1/2"**	**5/8"**	**3/4"**
1-1/2"	6	–	–
1-3/4"	12	18	18
2"	6	–	–
2-1/8"	–	6	–
2-1/4"	–	–	6
2-3/4"	12	12	6
3-1/4"	–	–	6

reduced thickness (reduction for top x reduction for bottom). It is evident that the cross-grain construction of plywood increases its lateral load capability above that of an equivalent thickness of lumber.

In lumber, the 1" minimum penetration published in the reference *(12)* did not develop load factors consistent with similar tests using nails. The test data indicated, however, that under full design load such load factors are developed at a minimum penetration of 2" (Table B-3, page 38). At lesser penetrations, adequate load factors are maintained by reducing design load proportionately, to a maximum reduction of 25 percent for 1" penetration (P/4 + 0.50).

Load factors achieved in individual tests as well as diaphragm tests indicate that the 30 percent increase applied to lateral nail design loads for diaphragm construction *(7)* is not warranted for staples.

Conclusions

The following minimum penetrations are required to develop 75-lb lateral load for 14-ga staples:

1. Plywood to NDS Group II lumber, specific gravity 0.50 or greater (Douglas-fir): 2" penetration, with proportionate reduction for less penetration to a minimum of 1".

2. Plywood to plywood (both layers STRUCTURAL I): 1/2" top layer and 5/8" substrate, with proportionate reductions for thinner plywood in either or both layers (reduction for top layer x reduction for substrate).

Part 2. Stapled Tongue and Groove

Staples driven through the T&G joint to transfer shear load to adjoining panels are feasible only with the T&G joint profile used with 1-1/8" APA STURD-I-FLOOR 48 oc (2-4-1) plywood. This joint has a tongue 7/8" long and 1/2" thick at its base. T&G joints for plywood up to 3/4" thick have tongues 3/8" long and less than 1/4" thick and, thus, are not recommended for transferring shear loads because of the impracticality of driving staples through the smaller T&G edges.

Test Summary

All tests used 16-gage bright staples. Crown width was 7/16" nominal.

Tests conducted in 1965 used 1-1/8" plywood and 1"-long staples. Plywood had all plies of Group 2 species. Nine specimens were tested, using three staple spacings. Average ultimate load was 267 lb per staple.

Tests conducted in 1978 used 7/8" plywood and 7/8"-long staples. Plywood had Group 1 face and back plies and Group 4 inner plies. The T&G joint was cut using the profile for 1-1/8" plywood, except it was centered on the 7/8" thickness. Eight specimens were tested, using two staple spacings. Average ultimate load was 317 lb per staple.

The lateral design load and load factors for T&G joints fastened with 16-ga bright staples may be determined as follows:

52 x 0.90 = 47 lb per staple
reduction for non-Structural I plywood
design lateral load *(12)*

Load Factors = 267/47 = 5.68; 317/47 = 6.74

Conclusions

Lateral design load for 16-ga staples may be used for stapled T&G joints.

Part 3. Fastener Slip

The equations in Table B-4 (page 38) are based on lateral load tests on nails and staples as reported in this Appendix, and those reported in 1952 *(1)*.

TABLE B-2

LATERAL LOADS FOR 14-ga BRIGHT STAPLES (PLYWOOD TO PLYWOOD)(1)

Plywood Thickness (in.)		Number of Tests	Ultimate Load (lb)		Recommended Design Load(2) (lb)	Load Factor
Top	Substrate		Range	Avg.		
3/8	1/2	6	203-269	236	45	5.24
	5/8	6	228-304	268	56	4.79
	3/4	6	228-336	288	56	5.14
1/2	1/2	6	243-369	319	60	5.32
	5/8	6	289-382	333	75	4.44
	3/4	6	319-440	388	75	5.17
5/8	1/2	6	182-321	269	60	4.48
	5/8	6	275-352	309	75	4.12
	3/4	6	328-411	373	75	4.97

(1) All plies were species Group 1.

(2) A minimum 1/2" top layer and 5/8" substrate is recommended to develop the design load of 75 lb per staple. Recommended design loads are based on a straight line reduction for thinner plywood in either or both layers (reduction for top x reduction for bottom).

TABLE B-3

LATERAL LOADS FOR 14-ga BRIGHT STAPLES (PLYWOOD(1) TO LUMBER)

Plywood Thickness (in.)	Staple Penetration (in.)	Number of Tests	Ultimate Load (lb)		Recommended Design Load(2) (lb)	Load Factor
			Range	Avg.		
1/2	1	6	185-232	211	56	3.77
	1-1/4	12	196-373	240	61	3.93
	1-1/2	6	219-248	231	66	3.50
	2-1/4	12	289-387	323	75	4.31
5/8	1-1/8	18	168-251	211	59	3.58
	1-1/2	6	237-306	263	66	3.98
	2-1/8	12	280-369	332	75	4.43
3/4	1	18	158-382	236	56	4.21
	1-1/2	6	214-327	261	66	3.95
	2	6	273-339	319	75	4.25
	2-1/2	6	315-395	350	75	4.67

(1) All plies were species Group 1.

(2) A penetration of 2" is recommended to develop the design load of 75 lb per staple. To obtain recommended design load for penetration of 1" (minimum) to 2", multiply by (P/4 + 0.50), where P is penetration.

TABLE B-4

FASTENER SLIP EQUATIONS

Fastener	Minimum Penetration (in.)	For Maximum Loads up to (lb)	Approximate Slip, e_n(in.)(a)(b)	
			Green/Dry	Dry/Dry
6d common nail	1-1/4	180	$(V_n/434)^{2.314}$	$(V_n/456)^{3.144}$
8d common nail	1-7/16	220	$(V_n/857)^{1.869}$	$(V_n/616)^{3.018}$
10d common nail	1-5/8	260	$(V_n/977)^{1.894}$	$(V_n/769)^{3.276}$
14-ga staple	1 to 2	140	$(V_n/902)^{1.464}$	$(V_n/596)^{1.999}$
14-ga staple	2	170	$(V_n/674)^{1.873}$	$(V_n/461)^{2.776}$

(a) Fabricated green/tested dry (seasoned); fabricated dry/tested dry. V_n = fastener load.

(b) Values based on Structural I plywood fastened to Group II lumber, specific gravity 0.50 or greater. Increase slip by 20% when plywood is not Structural I.

APPENDIX C

Derivation of Design Shear Equation for Discontinuous Interior Panel Joints

When interior panel joints parallel to the applied lateral load are discontinuous, as in Case 1 and Case 2 diaphragms, shear resistance may be satisfied by fastening reduced from that at the boundary. For diaphragm shears exceeding those recognized by model codes prior to 1980 (shown in Table A-1 of Appendix A), a check must be made to assure that the continuous panel is not overstressed in shear-through-the-thickness due to load distribution resulting from the mechanically fastened panels. An equation is derived in this Appendix to make this check.

Figure C-1 shows relationships used in the derivation. Terms are as follows:

ℓ = center-to-center spacing of framing (in.), which is the minimum possible distance between staggered panel joints.

V_{cp} = shear in continuous panel (plf).

V_{np} = shear in panel with joint (plf).

A = shearing area per foot of panel, $12t$ (in.^{2}).

t = plywood effective thickness for shear (in.), from PDS *(8)*.

G = modulus of rigidity of panel (psi), from PDS *(8)*.

e_n = fastener slip (in.), from Appendix B.

V_n = fastener design load (lb).

n = fasteners per foot.

F_v = plywood design shear-through-the-thickness stress (psi), from PDS *(8)*.

Figure C-1 represents a diaphragm element A-B-C-D acted upon by shearing stresses of intensity v applied along A-B and C-D. Because of the action of these stresses, the element is deformed to A_1-B_1-C_1-D_1

The modulus of elasticity in shear (G) is equal to the unit shearing stress divided by the unit shearing strain. In Figure C-1, y_s represents the shearing strain (deflection); therefore, $y_s/(\ell/2)$ represents the unit shearing strain. Thus,

$$G = \frac{v}{ys/(\ell/2)} = \frac{\text{unit shearing stress}}{\text{unit shearing strain}}$$

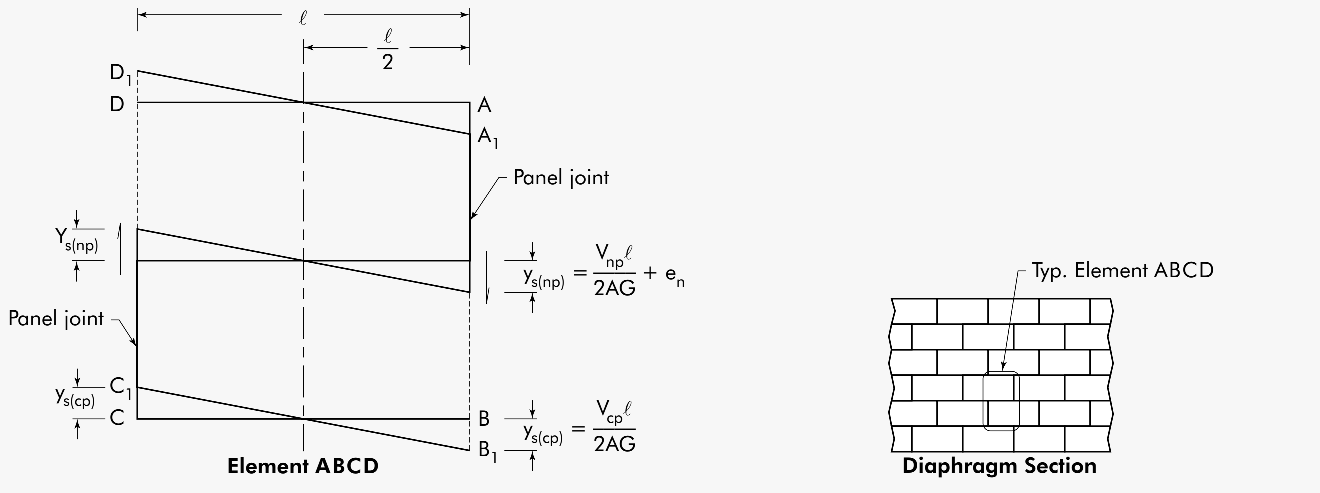
from which $y_s/(\ell/2) = v/G$.

The shear stress $v = V/A$, where V is the shear force on the section due to external (wind or seismic) forces, and A (= 12t) is the cross sectional area of the plywood. Therefore, $y_s/(\ell/2) = V/AG$ and $y_s = V\ell/2AG$.

For full-scale diaphragms, ℓ is usually a small portion of the overall diaphragm dimension. Therefore, a simplifying assumption is made that the shear force (V) along A-B and that along C-D are approximately equal.

FIGURE C-1

DIAPHRAGM ELEMENT ILLUSTRATING SHEARING STRAIN (y_s) OF CONTINUOUS PANELS AND PANELS WITH JOINTS ALONG ADJACENT SUPPORTS.



The total shear force on the section is resisted by both continuous panels and panels with joints, in proportion to their shear strain. In the case of panels with joints, the shear strain includes the effect of fastener slip due to the shearing forces. Therefore, the portion of shear force resisted by both types of panels is determined by equating the shearing strain of each along A-B (or C-D), measured relative to the axis of symmetry at the mid-width of the panel between supports:

$$y_{s(cp)} = y_{s(np)}$$

Therefore, referring to Figure C-1:

$$\frac{V_{cp}\ell}{2AG} = \frac{V_{np}\ell}{2AG} + e_n$$

from which

$$V_{cp} = V_{np} + \frac{e_n(2AG)}{\ell}$$

However, $V_{np} = nV_n$ [1]

Substituting Equation [1] and $A = 12t$:

$$V_{cp} = nV_n + \frac{e_n(24Gt)}{\ell} \qquad [2]$$

However, the value of V_{cp} cannot exceed the shear capacity of the panel, which is $12F_vt$. Therefore, Equation [2] can be rewritten as

$$12F_vt = nV_n + \frac{e_n(24Gt)}{\ell}$$

To determine the maximum value of V_n without exceeding the shear capacity of the panel, the term

$$e_n = \left(\frac{V_n}{K}\right)^a \qquad [3]$$

is substituted into Equation [2], with a and K as defined in Table B-4 of Appendix B. Choosing various values of V_n, a trial and error solution is used to determine a value of V_n (to the nearest lb). Using this value of V_n, and the corresponding value of e_n from Table B-4 of Appendix B, the shear capacities of the panels with joints (V_{np}) and the continuous panels (V_{cp}) can be calculated from Equations [1] and [2], respectively.

The recommended design shear (V) along the discontinuous interior panel joints is the average of V_{cp} and V_{np}:

$$V = \frac{V_{np} + V_{cp}}{2} = nV_n + \frac{12\ Gt\ e_n}{\ell} \qquad [4]$$

in which V_n and e_n are determined from Equation [3].

In deriving the design shears given in Table 1 of this report, calculations were made using e_n values for nailed green, tested dry; then for nailed dry, tested dry (see Table B-4 of Appendix B). The lower of the two resulting design shears was tabulated.

APPENDIX D

Load Deflection Curves for Test Diaphragms

The following pages contain load-deflection curves for all the diaphragms covered in the body of this report, (Figures D-1 through D-11). The curves trace the first loading cycle to test load, the first cycle to twice test load, then the cycle to ultimate load to the extent deflection was measured. Intermediate repetitive loadings are omitted for clarity.

FIGURE D-1

DIAPHRAGM 1 – 1/2" APA STRUCTURAL I RATED SHEATHING 32/16
CASE 2 PANELIZED; 10d COMMON 4, 6, 12 o.c.

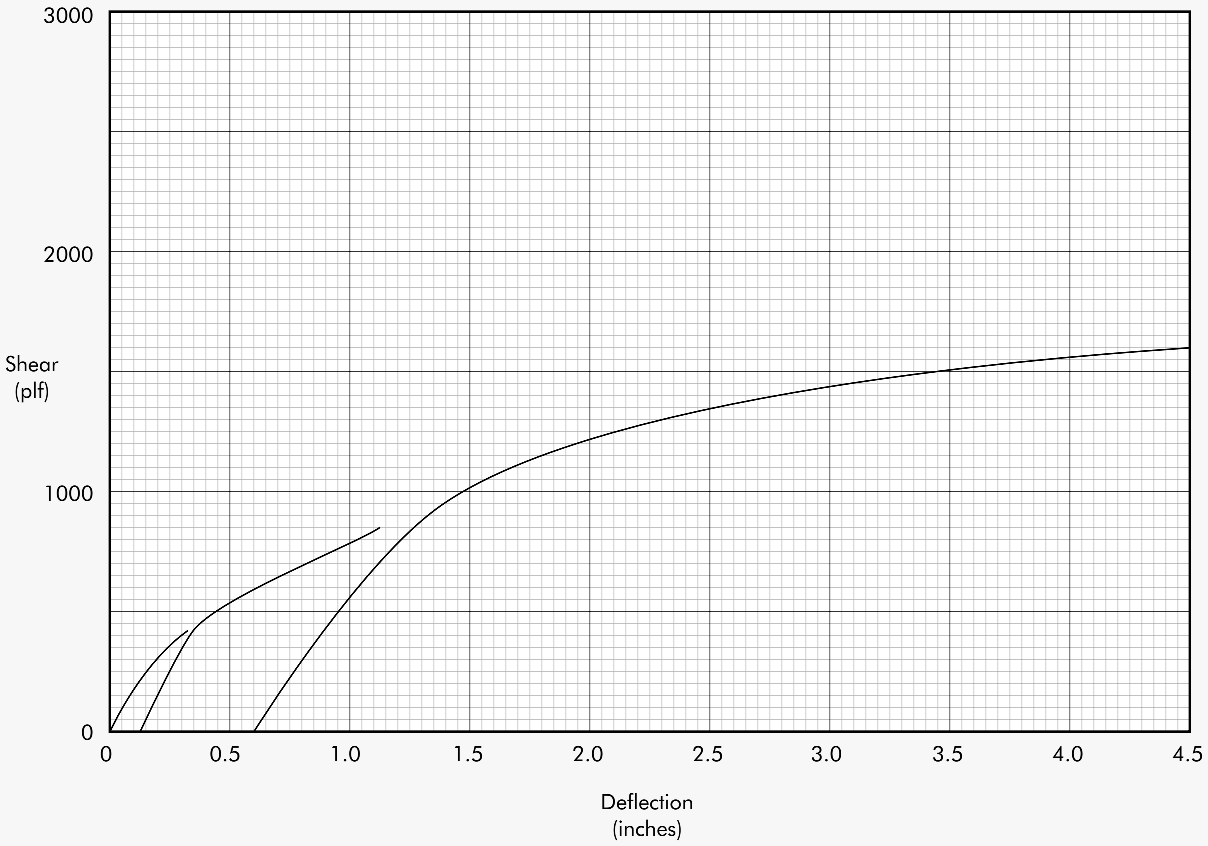


FIGURE D-2

DIAPHRAGM 2 – 2 LAYER, 1/2" APA STRUCTURAL I RATED SHEATHING 32/16

CASE 2 PANELIZED (WITH PARTIAL ADDED TOP LAYER); TOP 10d COMMON 4 o.c. (BOUNDARY), 14-ga STAPLES 3, 12 o.c.; BOTTOM 10d COMMON 4, 6, 12 o.c.

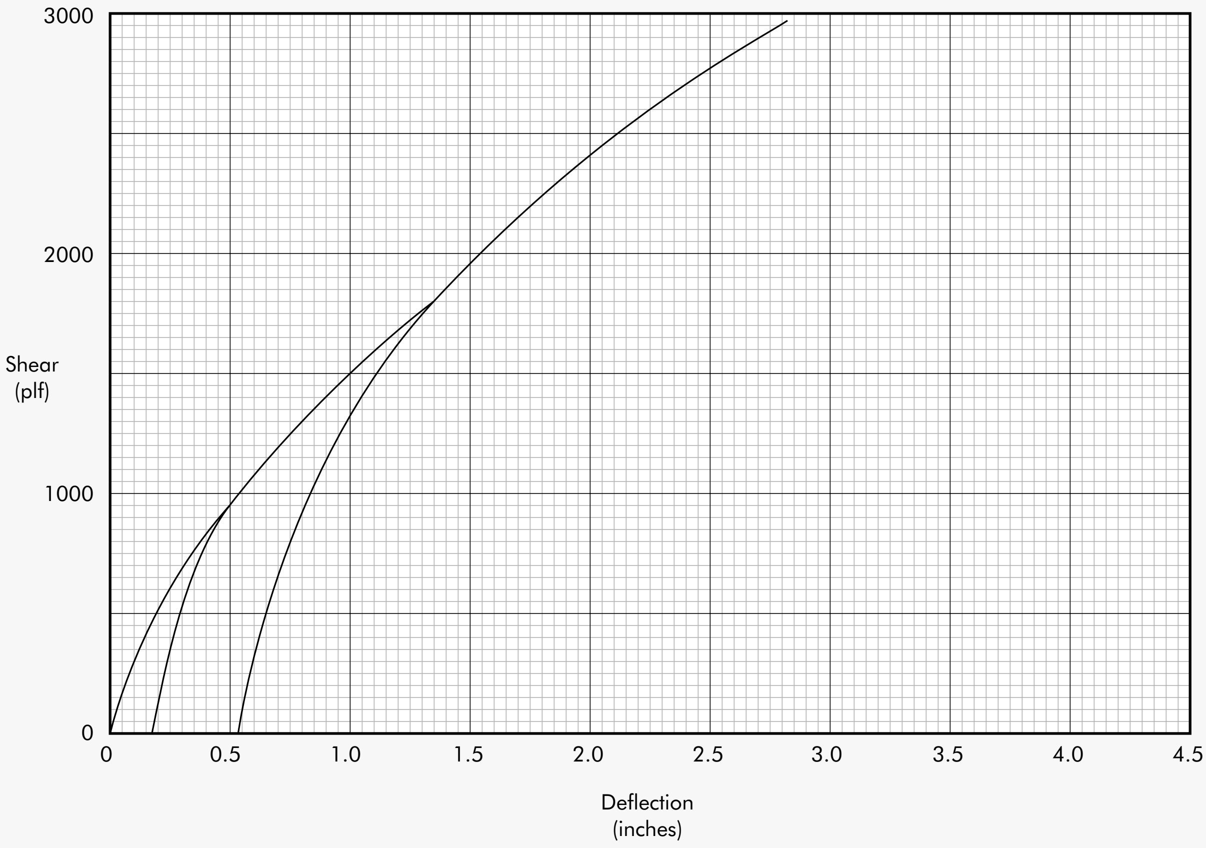


FIGURE D-3

DIAPHRAGM 3 – 4' x 4' OPENING, 1/2" APA STRUCTURAL I RATED SHEATHING 32/16

CASE 2 PANELIZED; 10d COMMON 4, 6, 12 o.c.

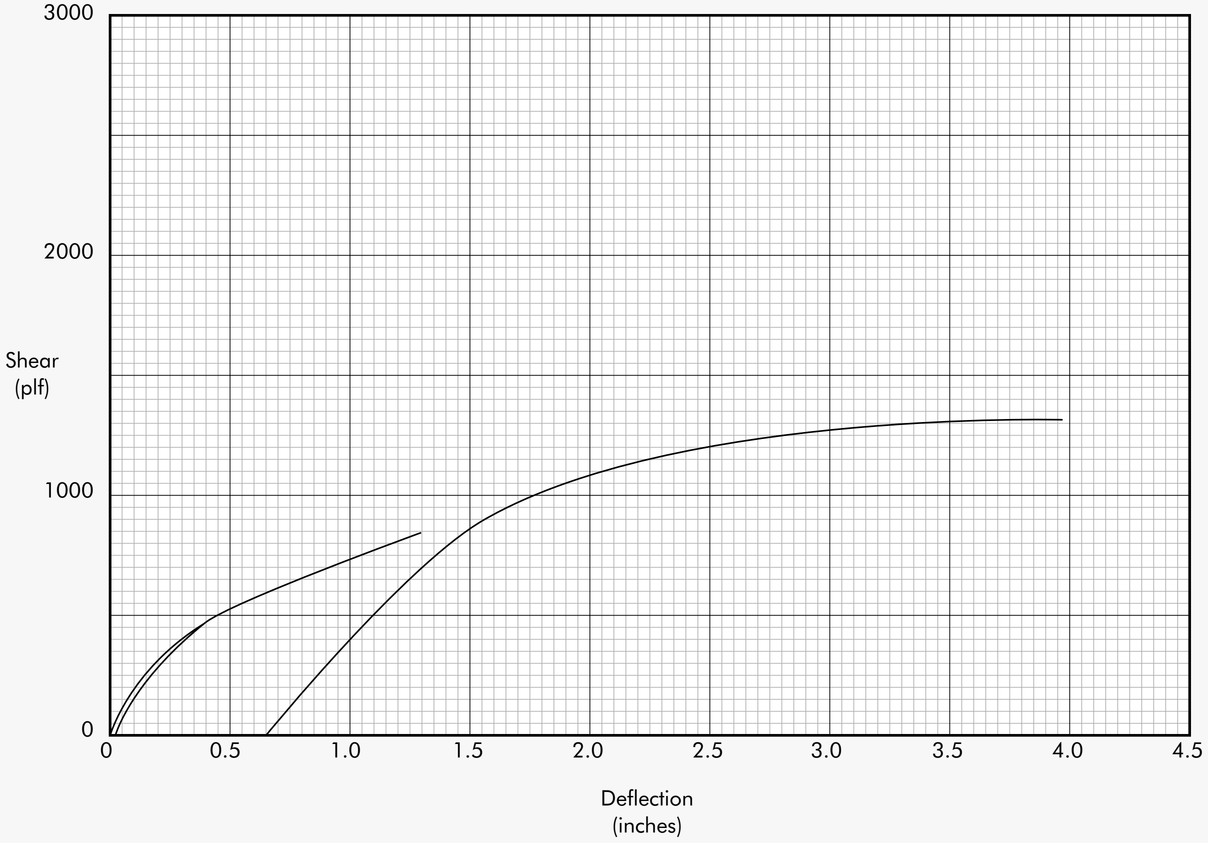


FIGURE D-4

DIAPHRAGM 4 – 8' x 8' OPENING, 1/2" APA STRUCTURAL I RATED SHEATHING 32/16

CASE 2 PANELIZED; 10d COMMON 4, 6, 12 o.c.

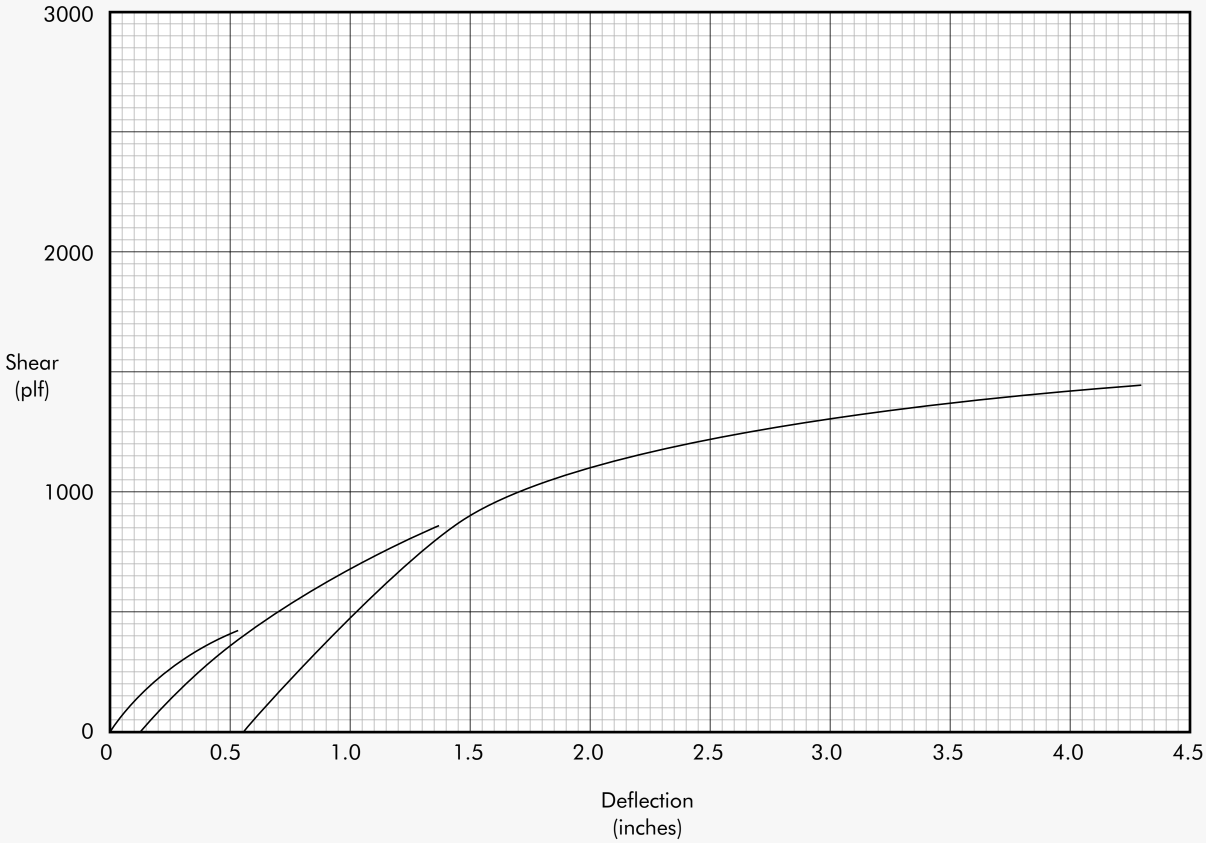


FIGURE D-5

DIAPHRAGM 5 – FIELD-GLUED, 1/2" APA STRUCTURAL I RATED SHEATHING 32/16

CASE 2 PANELIZED; 10d COMMON 12, 12, 12 o.c.

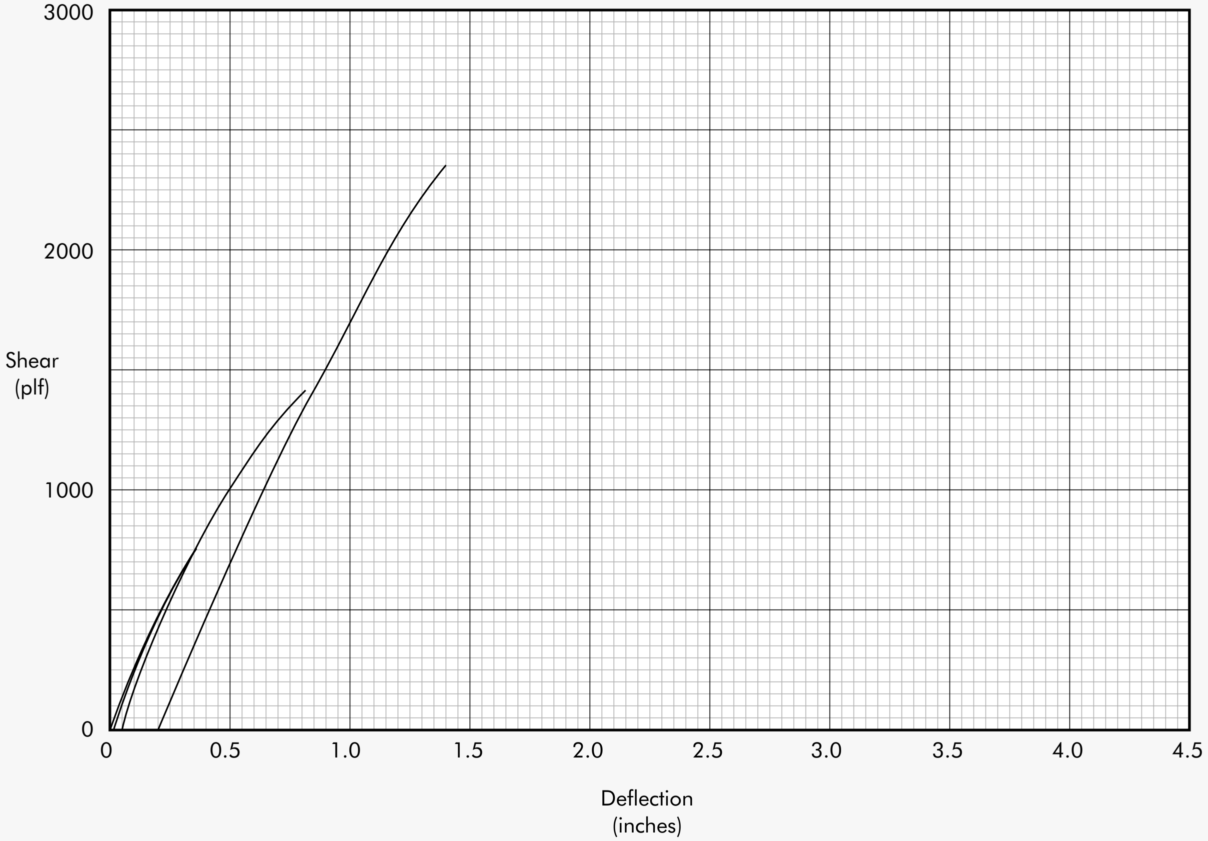


FIGURE D-6

DIAPHRAGM 6 – FIELD-GLUED, 5/8" APA STRUCTURAL I RATED SHEATHING 42/20 (NOW 40/20)

CASE 1, JOISTS 32" o.c.; 8d COMMON 12, 12, 12 o.c.

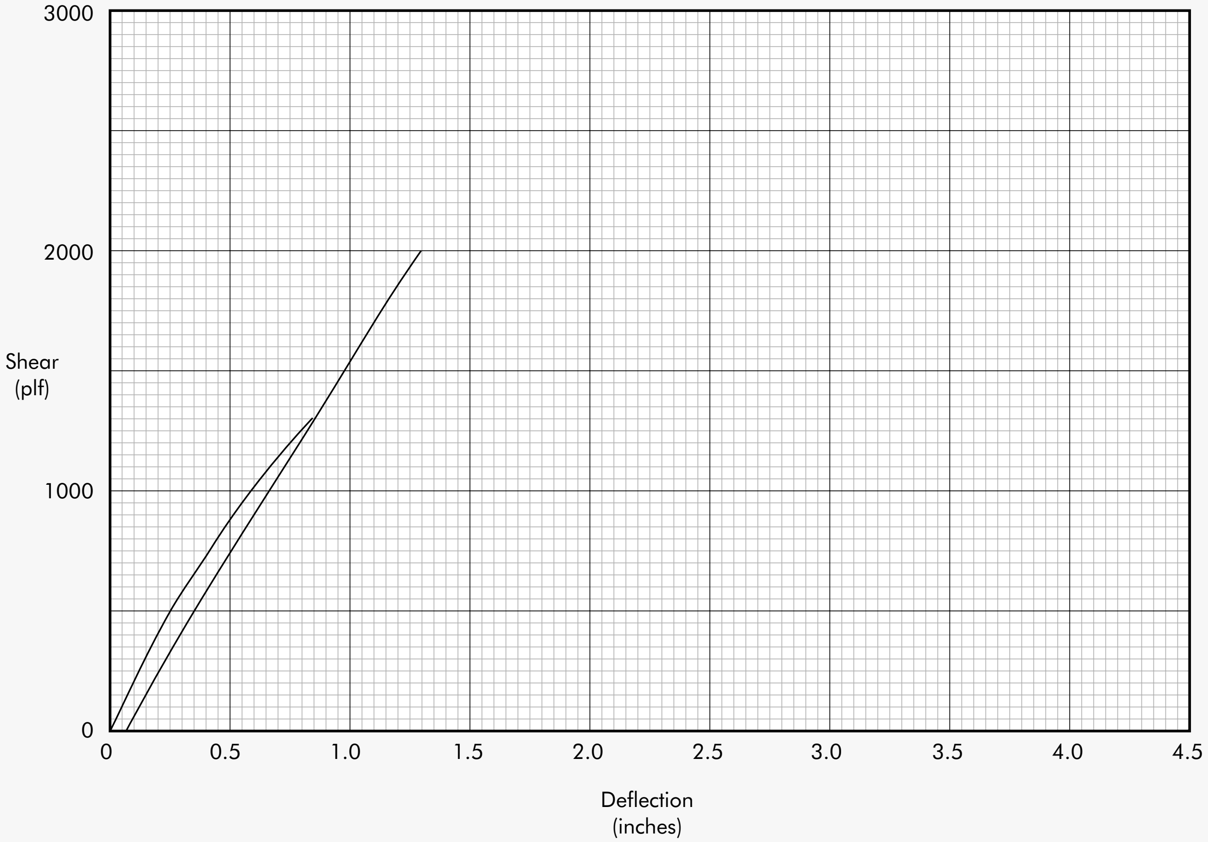


FIGURE D-7

DIAPHRAGM 7 – 5/8" APA STRUCTURAL I RATED SHEATHING 42/20 (NOW 40/20)

CASE 1, JOISTS 32" o.c.; 14-ga x 1-3/4" STAPLES, BOUNDARY 2" o.c. x 3 ROWS, PANEL EDGES 1" o.c., PANEL INTERIOR 6" o.c.

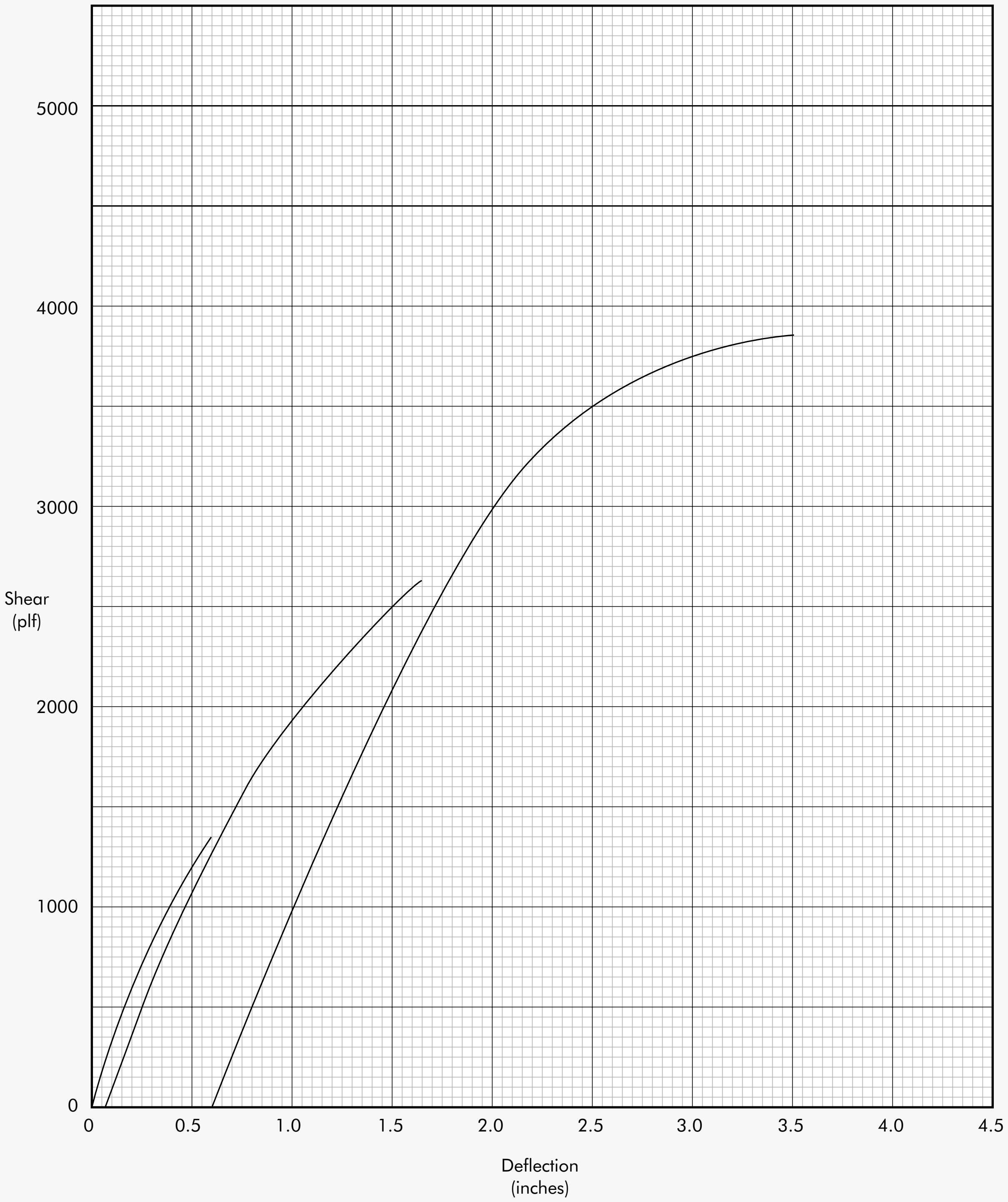


FIGURE D-8

DIAPHRAGM 8 – 3/4" APA STRUCTURAL I RATED SHEATHING 48/24

CASE 1, JOISTS 48" o.c.; 14-ga x 2-3/4" STAPLES, BOUNDARY 1-1/2" o.c. x 3 ROWS, PANEL EDGES 1-1/2" o.c. x 2 ROWS, PANEL INTERIOR 3" o.c.

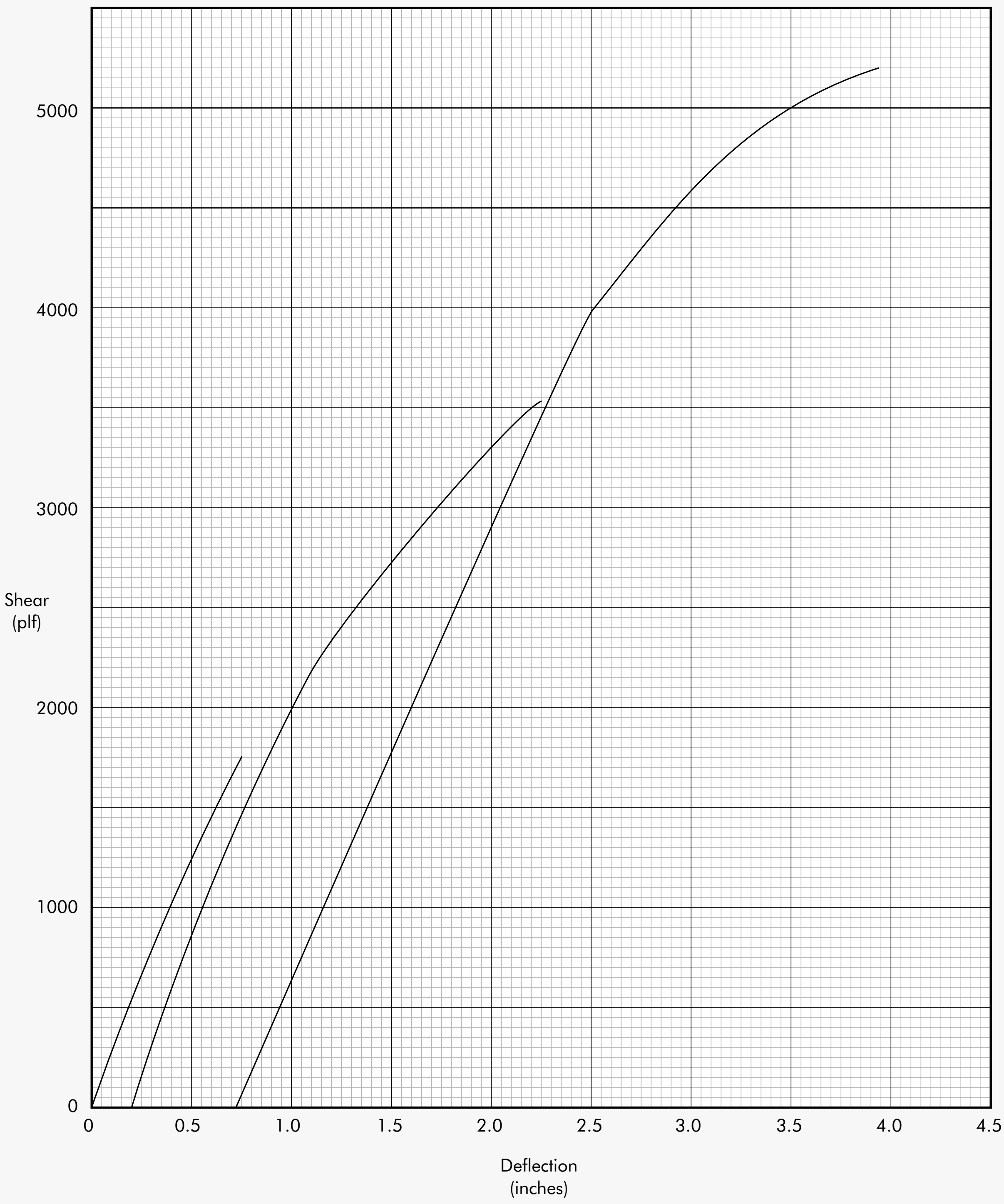


FIGURE D-9

DIAPHRAGM 9 – 3/4" APA STRUCTURAL I RATED SHEATHING 48/24

CASE 1, JOISTS 48" o.c.; 10d SHORT (0.148" DIA. x 2-1/4" LONG), BOUNDARY 3" o.c. x 3 ROWS, PANEL EDGES 3" o.c. x 2 ROWS, PANEL INTERIOR 6" o.c.

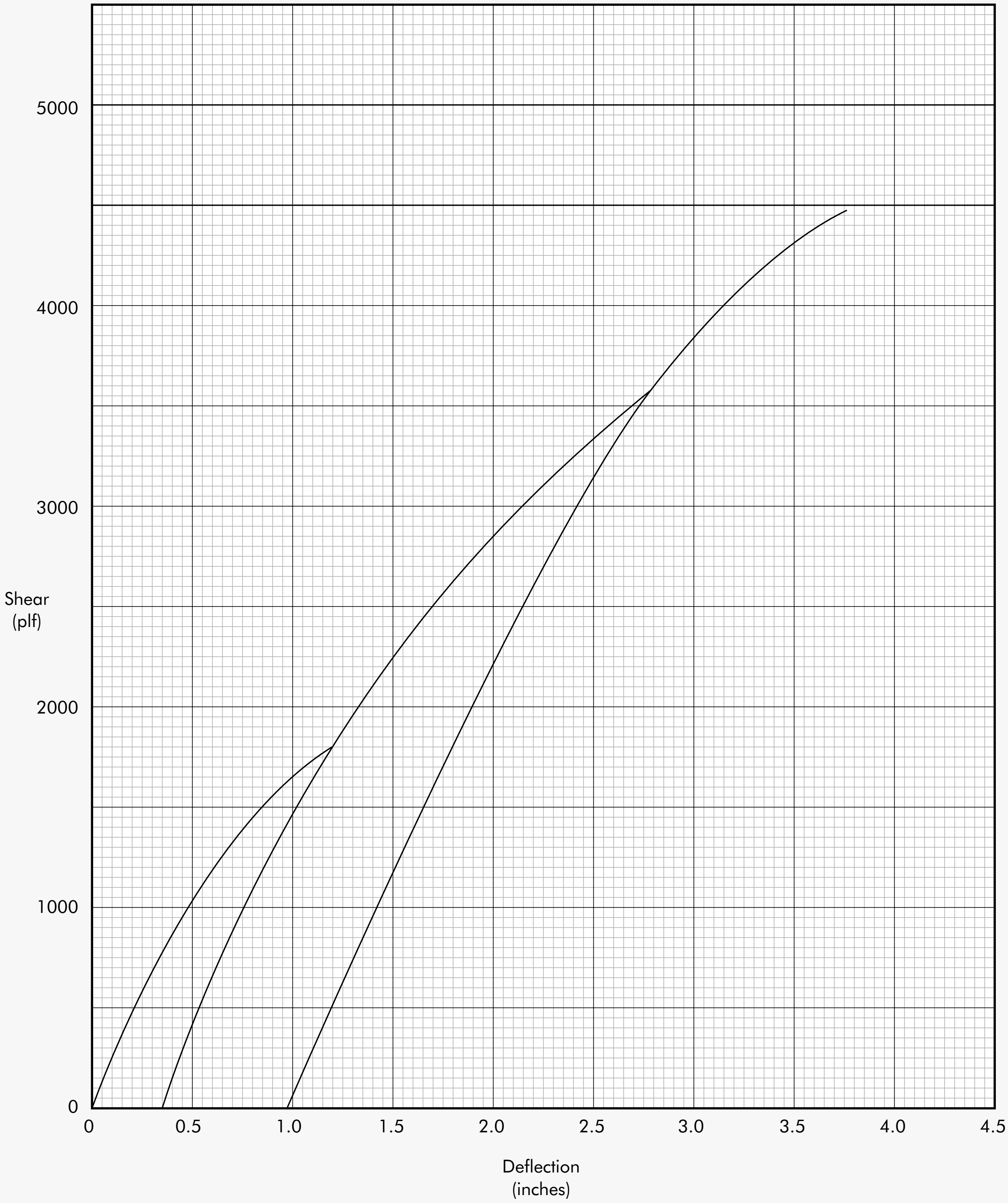


FIGURE D-10

DIAPHRAGM 10 – 3/4" APA STRUCTURAL I RATED SHEATHING 48/24

CASE 1, JOISTS 48" o.c.; 10d SHORT (0.148" DIA. x 2-1/4" LONG), BOUNDARY 3" o.c. x 3 ROWS, PANEL EDGES 3" o.c. x 2 ROWS, PANEL INTERIOR 6" o.c.

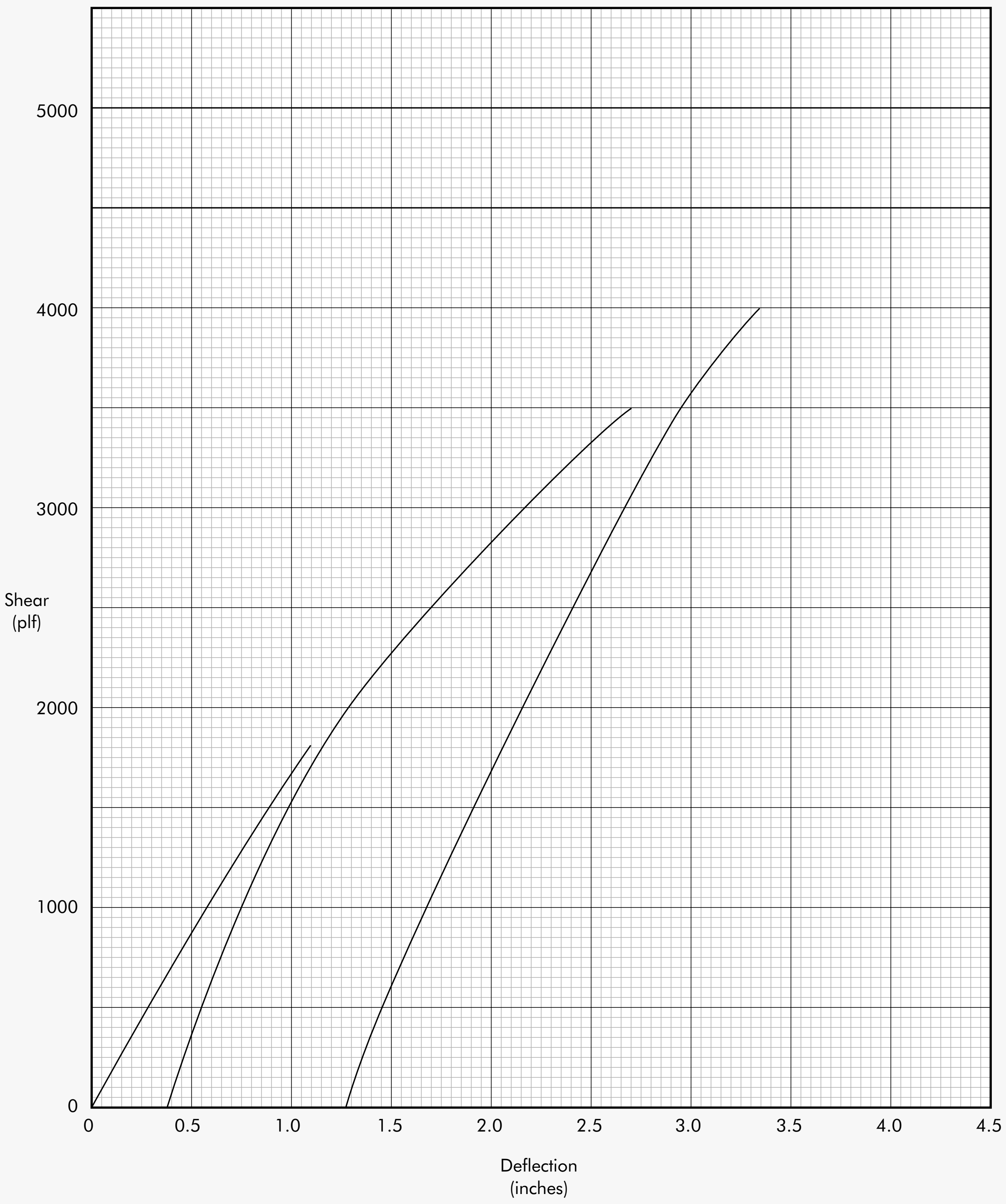
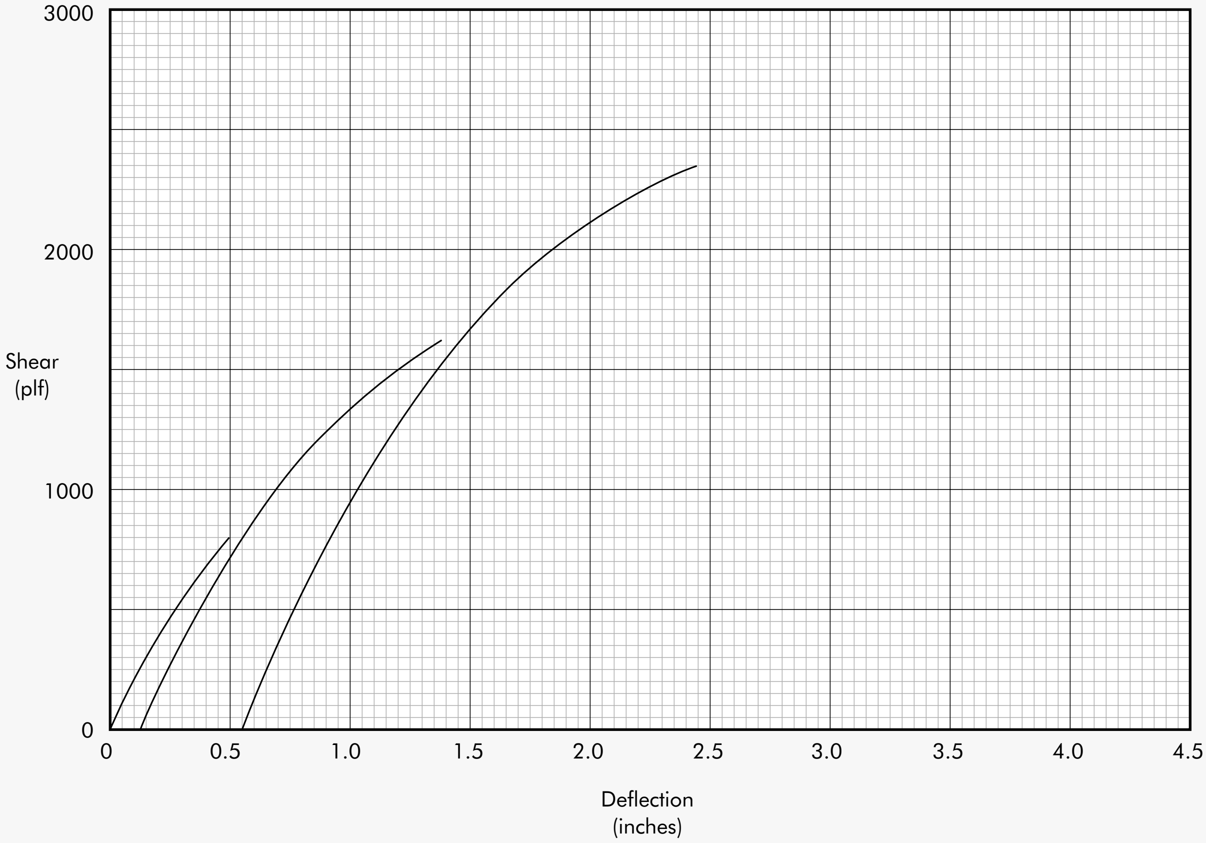


FIGURE D-11

DIAPHRAGM 11 – 7/8" C-D WITH T&G EDGES (NOW DESIGNATED APA RATED SHEATHING 60/32)

CASE 1, JOISTS 60" o.c.; 14-ga x 2-3/8" STAPLES, BOUNDARY 3" o.c. x 2 ROWS, PANEL ENDS 2" o.c., PANEL INTERIOR 6" o.c.; 16-ga x 1" STAPLES, PANEL EDGE T&G JOINT 1" o.c.



APPENDIX E

Analysis of Chord Forces and Shears for Diaphragm 4

This analysis of forces in Diaphragm 4, which included two symmetrical 8-ft x 8-ft openings, is based on a design method described in ATC-7, Guidelines for the Design of Wood Sheathed Diaphragms, developed by the Applied Technology Council (Redwood City, California).

The analysis assumes that a diaphragm with openings behaves similar to a Vierendeel Truss. Observations and results of tests of diaphragms with openings (Diaphragms 3 and 4) support this assumption.

Figure E-1 is a plan view of Diaphragm 4 showing dimensions, external loads and locations of interest in subsequent calculations.

In the analysis, shear acting downward on the right-hand edge of the segment to the left of a cross section, or upward on the left-hand edge of the segment to the right of the cross section, is considered positive.

1. The diaphragm is first analyzed without consideration of the openings to obtain chord and web forces (See Figure E-1.)

Line 1:

$$R = V_1 = \frac{wL}{2} = \frac{290(48)}{2} = +6960 \text{ lb, or } +435 \text{ plf}$$

Line 2:

$$V_2 = w\left(\frac{L}{2} - x\right) = 290\left(\frac{48}{2} - 6\right) = +5220 \text{ lb, or } +326 \text{ plf}$$

$$M_2 = \frac{wx}{2}(L - x) = \frac{290(6)}{2}(48 - 6) = 36540 \text{ ft-lb}$$

$$F_2@\,a = \frac{M}{16} = \frac{36540}{16} = 2284 \text{ lb C; } F_2@\,d = 2284 \text{ lb T}$$

Line 3:

$$V_3 = 290\left(\frac{48}{2} - 10\right) = +4060 \text{ lb, or } +254 \text{ plf}$$

$$M_3 = \frac{290(10)}{2}(48 - 10) = 55100 \text{ ft-lb}$$

$$F_3@\,a = \frac{55100}{16} = 3444 \text{ lb C; } F_3@\,d = 3444 \text{ lb T}$$

Line 4:

$$V_4 = 290\left(\frac{48}{2} - 14\right) = +2900 \text{ lb, or } +181 \text{ plf}$$

$$M_4 = \frac{290(14)}{2}(48 - 14) = 69020 \text{ ft-lb}$$

$$F_4@\,a = \frac{69020}{16} = 4314 \text{ lb C; } F_4@\,d = 4314 \text{ lb T}$$

Line 5:

$$V_5 = 290\left(\frac{48}{2} - 16\right) = +2320 \text{ lb, or } +145 \text{ plf}$$

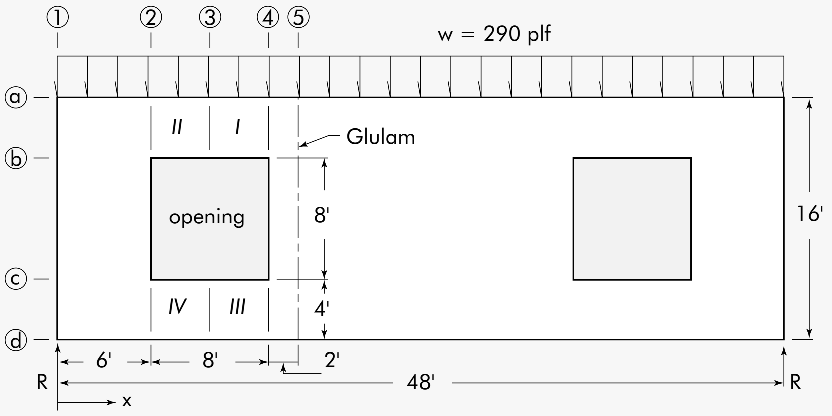
$$M_5 = \frac{290(16)}{2}(48 - 16) = 74240 \text{ ft-lb}$$

$$F_5@\,a = \frac{74240}{16} = 4640 \text{ lb C; } F_5@\,d = 4640 \text{ lb T}$$

2. The chord elements between shear webs of the Vierendeel Truss are assumed to have points of contraflexure at their mid-lengths. The boundary chord force at that location ($F_3@$ a and d) is calculated on the basis of the loaded diaphragm without openings, while the force in the chord at the edge of the opening ($F_3@$ b and c) is zero. The shears and chord forces at the edges of the opening are determined by using free-body sketches, as in Figure E-2. (Values summarize results of calculations which follow.)

FIGURE E-1

PLAN VIEW OF DIAPHRAGM 4



Segment I:

$F_3@\,a = 3444$ lb C; $F_3@\,b = 0$

$$V_{4(ab)} = \frac{V_4}{2} = \frac{+2900}{2} = +1450 \text{ lb, or } +363 \text{ plf}$$

$V_{3(ab)} = 1450 + 4(290) = +2610$ lb, or $+653$ plf

$F_4@\,a = [4(3444) + 4(1450) + 2(4)(290)]/4 = 5474$ lb C

$F_4@\,b = 5474 - 3444 = 2030$ lb T

Segment II:

$F_3@\,a = 3444$ lb C; $F_3@\,b = 0$

$V_{3(ab)} = +2610$ lb, or $+653$ plf (from Segment I)

$V_{2(ab)} = 2610 + 4(290) = +3770$ lb, or $+943$ plf

$F_2@\,a = [4(2610) + 2(4)(290) - 4(3444)]/4 = 254$ lb C

$F_2@\,b = 3444 - 254 = 3190$ lb C

Segment III:

$F_3@\,c = 0$; F3@ d = 3444 lb T

$$V_{4(cd)} = \frac{2900}{2} = +1450 \text{ lb,}$$

or $+363$ plf

$V_{3(cd)} = +1450$ lb, or $+363$ plf

$$F_4@\,c = \frac{4(1450)}{4} = 1450 \text{ lb C}$$

$F_4@\,d = 3444 + 1450 = 4894$ lb T

Segment IV:

$F_3@\,c = 0$; $F_3@\,d = 3444$ lb T

$V_{3(cd)} = +1450$ lb, or $+363$ plf
(from Segment III)

$V_{2(cd)} = +1450$ lb, or $+363$ plf

$$F_2@\,c = \frac{4(1450)}{4} = 1450 \text{ lb T}$$

$F_2@\,d = 3444 - 1450 = 1994$ lb T

The 8-ft openings in Diaphragm 4 measured 50 percent of its total width. Such large openings make it necessary to determine their effects on 1) framing members at the edges of the openings parallel to the diaphragm end chords, and 2) shear distribution in the plywood web. The following analysis is based on a design method developed by Edward F. Diekmann, C.E., S.E., consulting structural engineer from Kensington, California.

3. Net changes to chord forces due to openings in the diaphragm are determined by combining results of Step 2 with chord forces for the diaphragm without openings (Step 1) (Table E-1, page 54).

4. These net changes to chord forces due to openings result in shear forces that must be dissipated into the diaphragm sheathing through the plywood fastenings.

FIGURE E-2

FREE-BODY DIAGRAMS OF DIAPHRAGM SEGMENTS ADJACENT TO OPENINGS. (SEE FIGURE E-1 FOR LOCATIONS.)

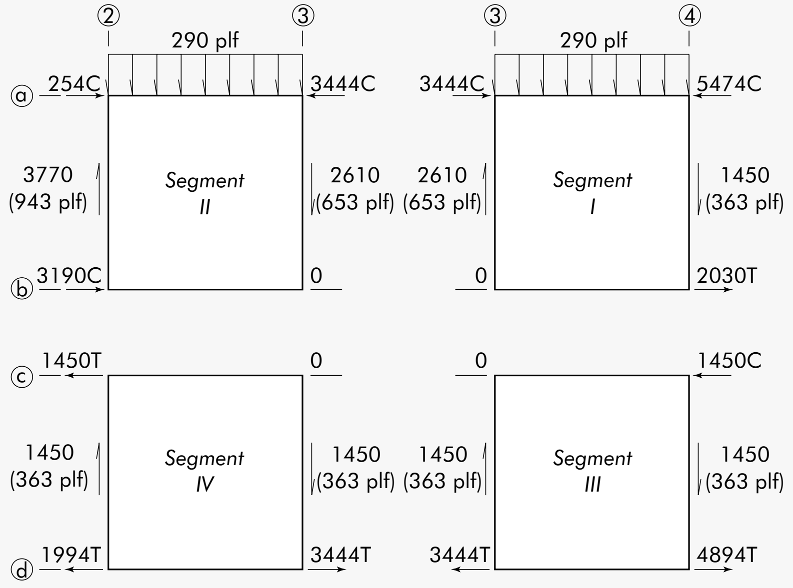
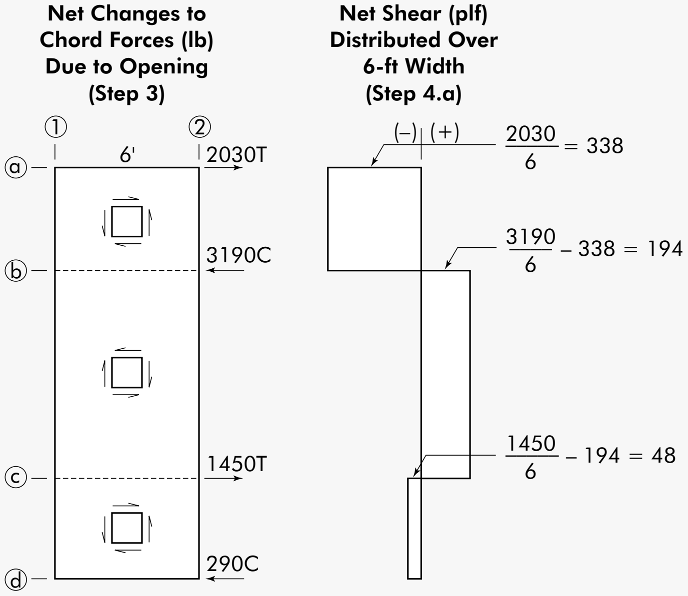


TABLE E-1

Diaphragm Force and Location	Chord Force (lb) Without Openings (Step 1)	Chord Force (lb) With Openings (Step 2)	Chord Force (lb) Net Change Due to Openings (Step 3)
F_2 @ a	2284 C	254 C	2030 T
F_2 @ b	0	3190 C	3190 C
F_2 @ c	0	1450 T	1450 T
F_2 @ d	2284 T	1994 T	290 C
F_4 @ a	4314 C	5474 C	1160 C
F_4 @ b	0	2030 T	2030 T
F_4 @ c	0	1450 C	1450 C
F_4 @ d	4314 T	4894 T	580 T

FIGURE E-3



a. In Diaphragm 4 the purlins at the edges of the openings parallel to the diaphragm length were continuous to the end chord, providing a 6-ft width between Lines 1 and 2 which can be utilized to distribute net shear forces (Figure E-3).

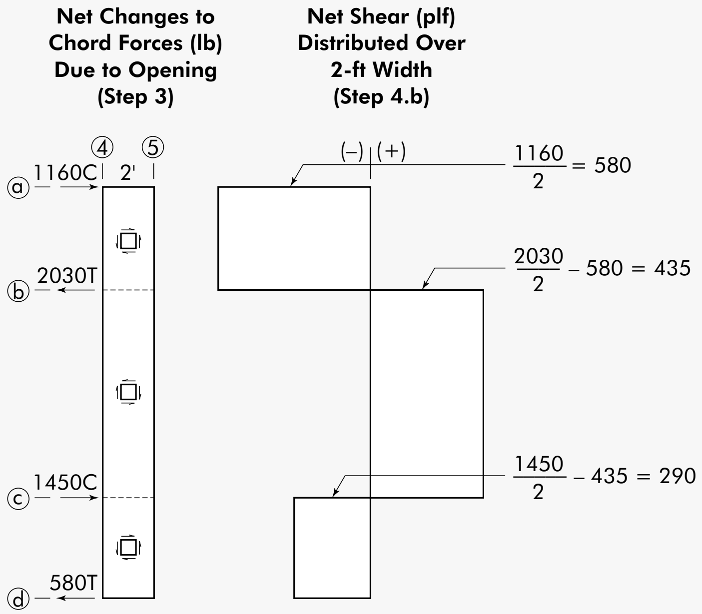
b. From Line 4 the purlins were continuous only for a distance of 2 feet to Line 5 (in Diaphragm 4, the tension splice over the glulam at Line 5 was not engineered to resist design stresses) (Figure E-4).

5. To determine resultant shears in the diaphragm, net shears due to openings are combined algebraically with shears for the diaphragm without openings (Table E-2).

6. To determine forces in the framing members bordering the openings parallel to the diaphragm end chords, shear forces either side of Lines 2 and 4 (from Steps 2 and 5) are combined (Figure E-5).

A splice connection should be designed to transfer these forces over the purlins (in Diaphragm 4, such splices were not provided).

FIGURE E-4

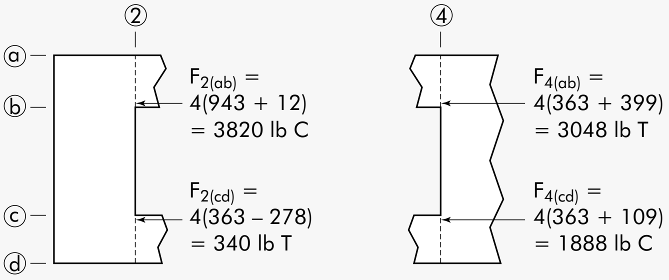

Net Changes to Chord Forces (lb) Due to Opening (Step 3)

Net Shear (plf) Distributed Over 2-ft Width (Step 4.b)

TABLE E-2

Diaphragm Shear and Location	Shear (plf)		
	Without Openings	Due to Openings	Resultant Shear
V_1 @ a to b	+ 435	– 338	+ 97
@ b to c	+ 435	+ 194	+ 629
@ c to d	+ 435	– 48	+ 387
V_2 @ a to b	+ 326	– 338	– 12
@ b to c	+ 326	+ 194	+ 520
@ c to d	+ 326	– 48	+ 278
V_4 @ a to b	+ 181	– 580	– 399
@ b to c	+ 181	+ 435	+ 616
@ c to d	+ 181	– 290	– 109
V_5 @ a to b	+ 145	– 580	– 435
@ b to c	+ 145	+ 435	+ 580
@ c to d	+ 145	– 290	– 145

FIGURE E-5



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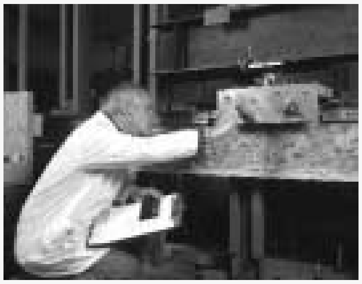

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