CROSS LAMINATED TIMBER

Horizontal Diaphragm Design Example

Our aim for this white paper is to provide a practical design method to determine the strength of a Cross Laminated Timber horizontal diaphragm and deflection due to lateral wind or seismic loads.

CLT HORIZONTAL DIAPHRAGM DESIGN

The design approach is based on compliance with engineered design of CLT in accordance with the 2015 International Building Code, reference standards, and other published information including manufacturer's literature.

Applicable Building Code, reference standards, and other information sources:

- *ICC, 2015 International Building Code*
- *ANSI/AWC NDS-2015 National Design Specification (NDS) for Wood Construction with Commentary*
- *AWC SDPWS-2015 Special Design Provisions for Wind and Seismic*
- *ANSI/APA PRG 320 – 2012 Standard for Performance-rated Cross-laminated Timber*
- *FP Innovations, US CLT (Cross-Laminated Timber) Handbook 2013*
- *ASCE 7-10 Minimum Design Loads for Buildings and Other Structures*
- *AISC 360-10 Specification for Structural Steel Buildings*
- *APA Product Report PR-L314 - CrossLam by Structurlam Products LP, February 20, 2014*
- *ICC-ES Evaluation Report ESR-3179 – ASSY Screws by MyTiCon Timber Connectors, October 2014*
- *Structurlam CrossLam Design Guide Imperial Version 11*
- *MyTiCon, CLT Connection Design Guide NDS*

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EXAMPLE DESCRIPTION

This example presents the design of a CLT diaphragm in a manner that is analogous to common methods for design of wood structural panel diaphragms including limitations on diaphragm aspect ratio. Shear transfer between adjacent CLT panels is through attachment to plywood splines with screws or nails. Good detailing practice for design of such diaphragms is based on design recommendations of the US CLT Handbook 2013. These recommendations suggest seismic force-resisting connections, including panel to panel diaphragm connections, be sized to develop NDS yield limit equation Mode III or Mode IV yielding behavior and that chords be designed with adequate strength to develop the shear strength of the diaphragm connections.

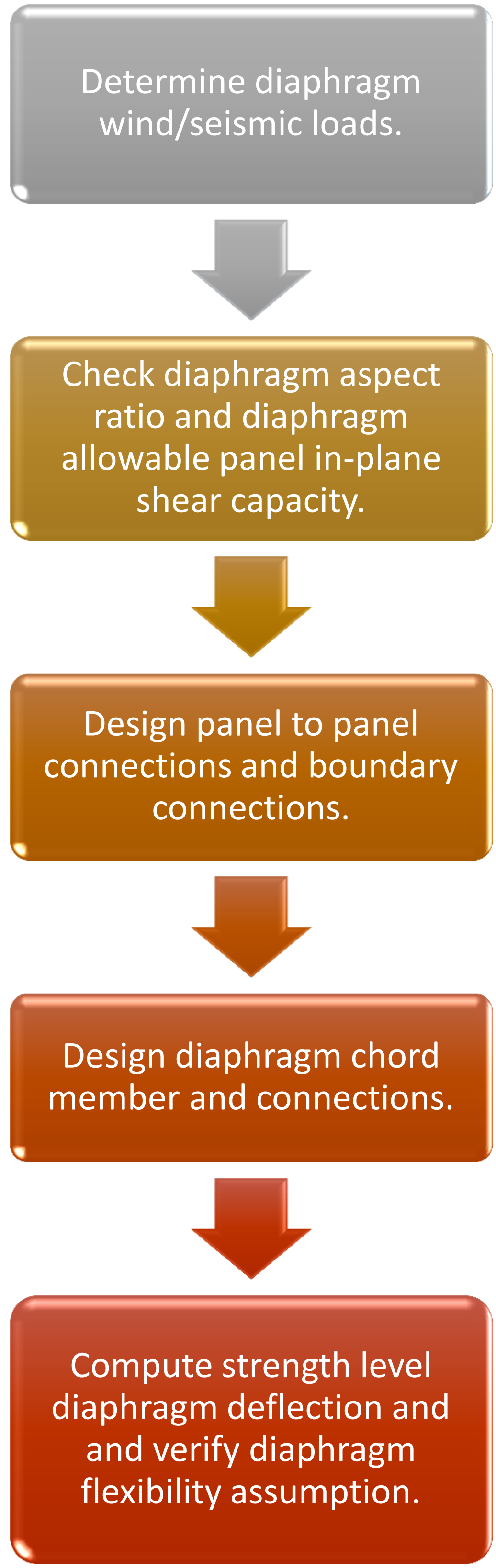
For the purposes of this example, CLT panels are designed and detailed to function as a continuous diaphragm chord. Panels functioning as the continuous chord are tied together with metal ties at panel joints.

While test-based design values of fastener strength and stiffness are available in the product evaluation report or manufacturer’s literature for the proprietary screws used in this example, strength and stiffness values are also determined in accordance with the NDS and NDS Commentary.

DIAPHRAGM DESIGN TIPS

1. For this example the CLT panel joints are continuous in north-south and east-west directions (e.g. non-staggered panel layout). A staggered panel layout, common in plywood diaphragms, is also an acceptable option for CLT diaphragms.
2. For this example a diaphragm chord splice is located at mid-span and associated with maximum chord forces. Locating chord splices away from the location of maximum diaphragm moment will reduce the chord splice force.

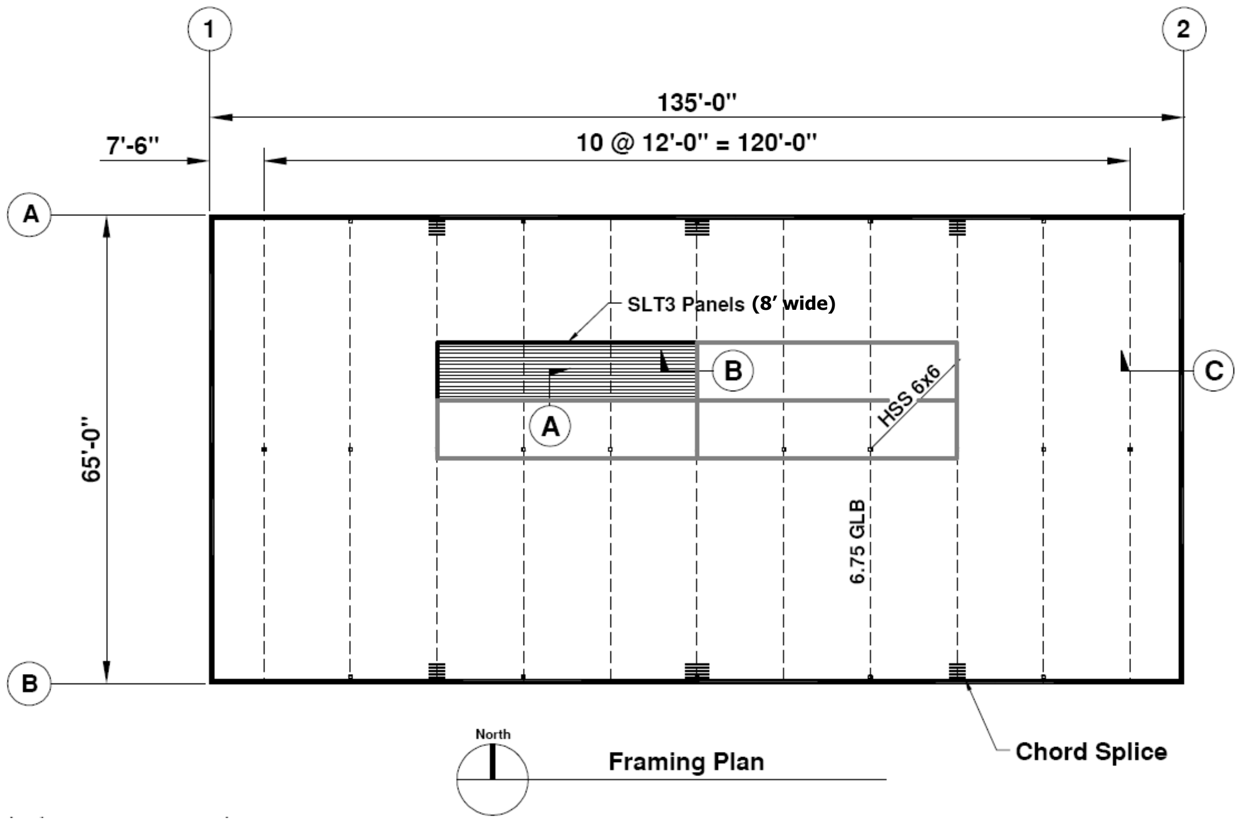
Diaphragm Design Flow Chart



3. For this example, fastener slip is the biggest contributor to diaphragm deflection but this may not be the case for all CLT diaphragms.
4. The diaphragm in this example utilizes a plywood spline connection for shear transfer between adjacent CLT panels. Diaphragm capacity employing plywood splines should not exceed the permissible capacities associated with nailed wood structural panel diaphragms given in AWC SDPWS-2015, unless verified by testing.
5. The deflection calculation method described in this example can be used to assist in making a determination of diaphragm flexibility in accordance with ASCE 7-10 (see ASCE 7-10 Section 12.3.1). For diaphragms that are not idealized as flexible, requirements for torsion (Section 12.8.4.1), accidental torsion (Section 12.8.4.2) and amplification of accidental torsional moment (Section 12.8.4.3) are applicable as well as limitations associated with torsional irregularity, if present.
6. 2015 IBC Section 1604 allows idealization of a diaphragm as rigid as follows - a diaphragm is rigid for the purpose of distribution of story shear and torsional moment when the lateral deformation of the diaphragm is less than or equal to two times the average story drift. Where a diaphragm is idealized as rigid, additional provisions of ASCE 7-10 are applicable as noted above.
7. The simplified seismic criteria of ASCE 7-10 Section 12.14 includes special criteria to address torsional effects which must be met as part of the method. These special criteria enable use of the simplified criteria without required checking of seismic drift and are applicable for designs that utilize diaphragms that are idealized as either flexible or rigid.
8. Consult your local building official on application of building code provisions for design of the CLT diaphragm before performing a final design (for example, to address acceptable use of proprietary values of fastener resistance).

CLT Horizontal Diaphragm Design Example

This design example is intended to evaluate a cross laminated timber diaphragm using Structurlam SLT3 Panels. The diaphragm strength and deflection is evaluated only in the north-south direction for seismic loads. The diaphragm is assumed to be flexible, but the assumption will be verified. Unless otherwise noted, the CLT diaphragm and connections are designed using allowable stress design loads while deflection due to seismic is based on strength design loads in accordance with ASCE 7. While not addressed in this example, special design force and detailing provisions for anchorage of concrete/masonry structural walls to diaphragms of ASCE 7 Section 12.11 are applicable for the design of CLT diaphragms. Additionally, the CLT splines should not be used to provide continuous cross ties required by Section 12.11.



Diaphragm Aspect Ratio

L/W = 135/65 = 2.07 < 4.0

Seismic Loads

Strength Level Design Load
w_{EQ} =1000 plf
Line 1 V_{EQ} = (1000)(135/2) = 67,500 lbs
v_{EQ} = 67,500/65 = 1038 plf

ASD Level Design Load
v_{EQ} = (0.7)67,500/65 = 727 plf

NOTE: *Diaphragm aspect ratio limit of 4.0 for CLT with plywood spline joints is based on extension of SDPWS-2015 Table 4.2.4 aspect ratio limit for blocked wood structural panel diaphragms.*

NOTE: *Design load was derived elsewhere and governs over wind loads.*

Panel Allowable In-Plane Shear Capacity

Vr = 2906 plf > 727 plf

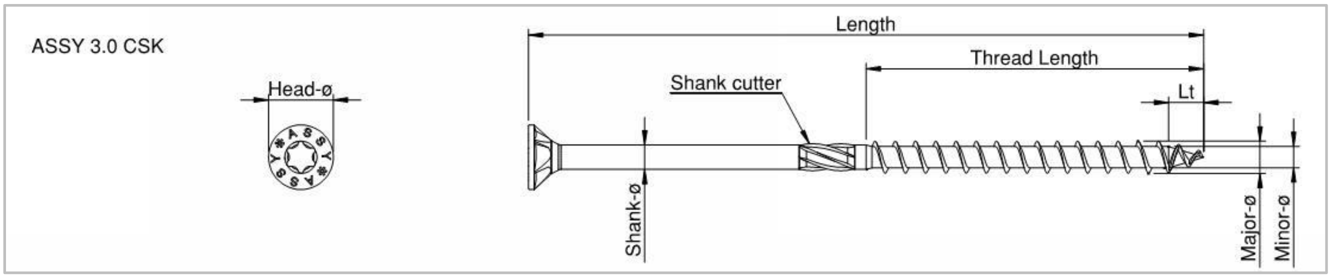
Shear Wall and Diaphragm Applications

CrossLam® In-Plane Allowable Shear Capacity				
Panel d (in)	SLT3 3.90	SLT5 6.66	SLT7 9.42	SLT9 12.18
	Vr (lbs/ft)			
	2906	5812	8718	11624

Reference: Structurlam CrossLam Design Guide Ver 12

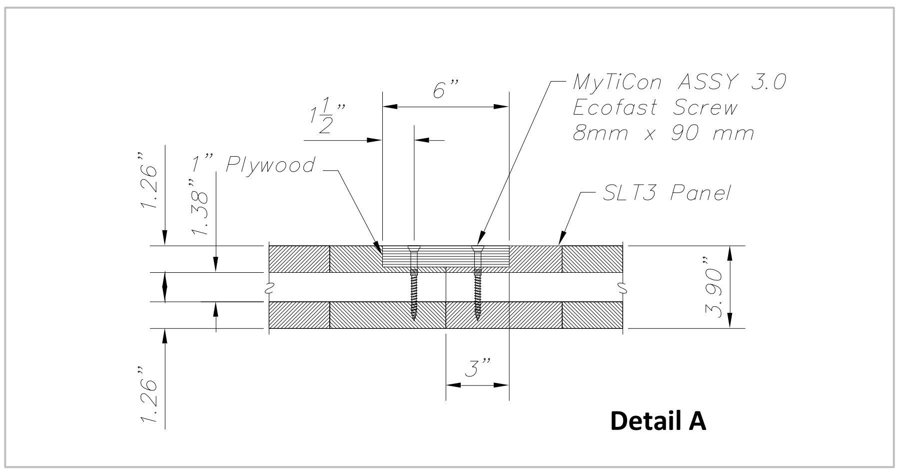
Panel to Panel Connection (Detail A with MyTiCon ASSY 3.0 Ecofast Screw)

***NOTE:** CLT panel in-plane shear capacity, Vr, is generally large compared to the panel to panel connection capacity.*



Reference: ICC-ES Evaluation Report ESR-3179 dated October 2014

Detail A with MyTiCon ASSY 3.0 Ecofast Screw



Detail A

Screw Diameter, D = Major Diameter = 8.0 mm (0.315 in.)
Shank Diameter = 5.8 mm (0.228 in.)
Minor Diameter = 5.3 mm (0.209 in.)
Screw Length, L = 90 mm (3.54 in.)

G = 0.42 *for Spruce-Pine-Fir STL3 Panel*
G = 0.42 *for plywood per NDS-2015 Table 12.3.3B*

***NOTE:** Minimum end distances, edge distances and spacing of the screws must be sufficient to prevent splitting of the wood and must conform to the ICC evaluation report and/or the manufacturer's recommendations. See ICC ESR 3179 Table 5. Consult the screw manufacturer for Cyclic testing results.*

Min Screw Spacing = 5d = (5)(0.315) = 1.57 in.
Min Penetration = 6d = (6)(0.315 in.) = 1.89 in.
Actual Penetration = 3.54 – 1.0 = 2.54 in.

ICC ESR 3179 Section 4.1.1

D_r = 0.209 in. (root diameter) *ICC ESR 3179 Table 1*
F_{YB} = 150,200 psi
ℓ_m = (3.54 in. screw length -1.0 in. plywood thickness)
= 2.54 in.
t_S = 1.00 in.
Z = 164 lbs (Mode IIIs) *NDS-2015 Section 12.3.1*
C_D = 1.60 *NDS-2015 Table 2.3.2*

Z' = 164(1.60) = 262 lbs
ASD Line 1 Shear = 727 plf
Required Spacing = (262)(12)/727 = 4.32 in.
Use 4 in. spacing.

The shear capacity is governed by the bending yield strength of the screw in the side member (Mode III_S). The capacity above uses the root diameter, but for cases where the screw shank diameter extends sufficiently beyond the shear plane, the shank diameter may be used in calculation of Z'. Using the shank diameter of 0.228 inch, Z = 178 lbs (Mode IIIs) which provides a 9% increase in capacity. For short term wind or seismic loading, Z' = 178(1.60) = 285 lb.

These same screws have been tested by MyTiCon with a SLT3 Panel and a 3/4" plwood spline. The allowable capacity based on dividing average test values by a factor of 5.0 (see ICC-ES AC233) results in Z = 242 lbs per screw. For short term wind or seismic loading, Z' = (242)(1.60) = 388 lbs. The NDS value of Z = 178 lbs and Z'=285 lbs for wind or seismic loading are conservative relative to test-based value of Z and Z'.

The panel to panel connection is designed using the maximum diaphragm shear at Line 1. Panel to panel connections can be varied in zones along the diaphragm span to reflect the reduced shear forces toward the center of the diaphragm.

Panel Allowable Shear Capacity at Routed Section

The rout for the plywood will reduce the shear capacity of the panel. The remaining capacity is based upon center lamination only.
V = (1.38 thick)(12.0 width)(135 psi Fv for SPF)(1.60 C_D)/1.5 = 2385 lbs/ft > 727 lbs/ft.

Panel to Panel Connection (Detail A with Nails)

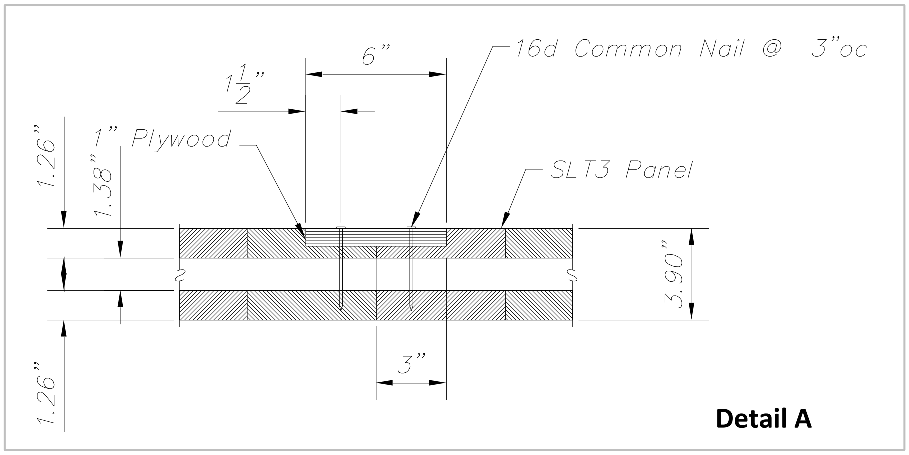
Use 1.0 in. plywood spline with 16d Common Nails (0.162" diameter x 3-1/2" long x 0.344" head diameter)

Z = 109 lb/nail *NDS-2015 Table 11R*
C_D = 1.60 *NDS-2015 Table 2.3.2*
C_{di} = 1.10 *NDS-2015 Section 12.5.3*
Z' = 109(1.60)(1.10) = 192 lbs *NDS-2015 Section 12.3.1*
Required Spacing = (192)(12)/727 = 3.16 in.
Use 3 in. spacing.
Minimum Nail Spacing = 15d = (15)(0.162) = 2.43 in. *NDS-2015 Table C12.1.6.6*

Side Member Thickness t_s in.	Nail Diameter D in.	Common Wire Nail	Box Nail	Sinker Nail	G=0.67 Red Oak lbs.	G=0.55 Mixed Maple Southern Pine lbs.	G=0.5 Douglas Fir-Larch lbs.	G=0.49 Douglas Fir-Larch (N) lbs.	G=0.46 Douglas Fir(S) Hem-Fir(N) lbs.	G=0.43 Hem-Fir lbs.	G=0.42 Spruce-Pine-Fir lbs.	G=0.37 Redwood (open grain) lbs.	G=0.36 Eastern Softwoods Spruce-Pine-Fir(S) Western Cedars Western Woods lbs.	G=0.35 Northern Species lbs.
		Pennyweight												
1	0.099[5]		6d	7d	56	53	51	50	49	48	47	44	44	43
	0.113[5]	*6d*[4]	8d	8d	73	68	66	66	64	62	61	58	57	56
	0.120[5]			10d	82	77	75	74	72	70	69	65	64	63
	0.128		10d		91	87	85	84	82	80	79	74	73	72
	0.131	8d			93	89	87	87	85	83	82	77	77	75
	0.135		16d	12d	97	93	91	90	89	87	86	82	81	80
	0.148	10d	20d	16d	109	104	101	101	99	97	96	91	91	90
	0.162	16d	40d		124	118	115	115	113	110	109	104	103	102
	0.177			20d	137	131	128	127	125	122	121	115	114	112
	0.192	20d		30d	141	135	131	131	128	125	124	118	117	116

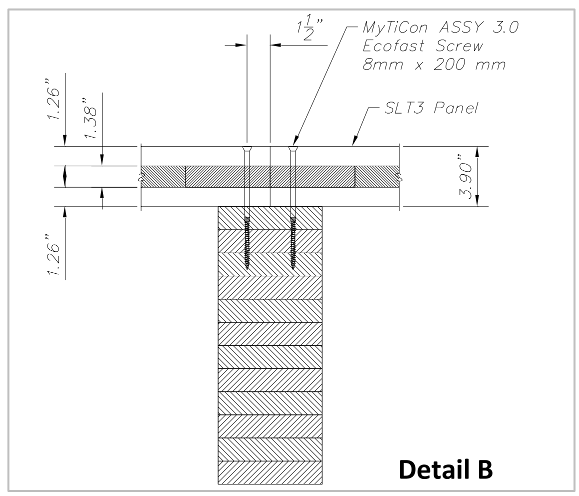
Reference: NDS Table 11R

Detail A with Nails



Panel Splice over Glulam Beam (GLB) (Detail B)

Z = 194 lbs for 5/16" x 7 1/8"(min) screw
G = 0.42 for SLT3 Panel
Side member thickness = 4.0 in.
Side member loaded perpendicular to grain and main member loaded parallel to grain.



C_D = 1.60 — *NDS-2015 Table 2.3.2*
Z' = (1.6)(194) = 310 lbs

Required Spacing = (310)(12)/727 = 5.12 in.
Use 5 in. spacing

NOTE: *Spacing based on 727 plf although a reduced shear force at the first interior GLB could be used.*

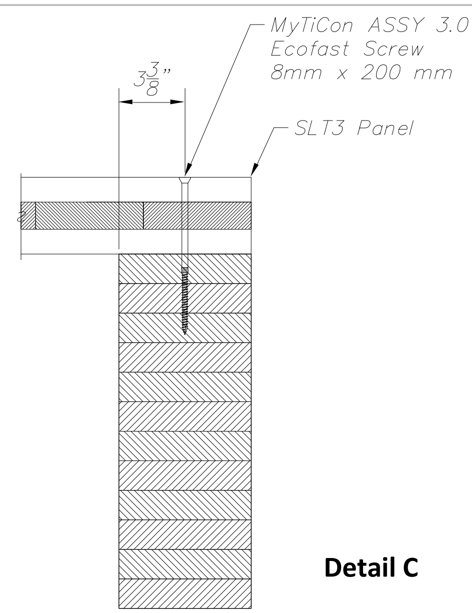
TABLE 2—REFERENCE LATERAL DESIGN VALUES (Z)[1,2,3,4,5]

FASTENER DESIGNATION[1]	SIDE MEMBER THICKNESS (inches)	FASTENER PENETRATION INTO MAIN MEMBER (inches)	REFERENCE LATERAL DESIGN VALUE, Z (lbf) FOR SPECIFIC GRAVITIES OF											
			0.33			0.42			0.49			0.55		
			$Z_{\parallel}$	$Z_{\perp/\parallel}$	$Z_{\perp}$	$Z_{\parallel}$	$Z_{\perp/\parallel}$	$Z_{\perp}$	$Z_{\parallel}$	$Z_{\perp/\parallel}$	$Z_{\perp}$	$Z_{\parallel}$	$Z_{\perp/\parallel}$	$Z_{\perp}$
1/4" x 4"	2	1 3/4	131	131	131	185	185	185	213	213	213	237	237	237
1/4" x 4 3/4"	2	2 1/2	142	142	142	185	185	185	213	213	213	237	237	237
1/4" x 5 1/2"	2 3/4	2 1/2	148	148	148	185	185	185	213	213	213	237	237	237
1/4" x 6 1/4"	3 1/2	2 1/2	148	148	148	185	185	185	213	213	213	237	237	237
1/4" x 7 1/8"	4	2 7/8	148	148	148	185	185	185	213	213	213	237	237	237
1/4" x 7 7/8"	5 1/2	2 1/8	148	148	148	185	185	185	213	213	213	237	237	237
1/4" x 8 5/8"	6	2 3/8	148	148	148	185	185	185	213	213	213	237	237	237
1/4" x 9 1/2"	7	2 1/4	148	148	148	185	185	185	213	213	213	237	237	237
1/4" x 11 3/4"	7 1/2	4	148	148	148	185	185	185	213	213	213	237	237	237
1/4" x 11 3/4"	8	3 1/2	148	148	148	185	185	185	213	213	213	237	237	237
1/4" x 11 3/4"	9	2 1/2	148	148	148	185	185	185	213	213	213	237	237	237
5/16" x 4 3/4"	2	2 7/16	164	131	131	234	187	187	280	224	224	311	249	249
5/16" x 5 1/2"	2 3/4	2 7/16	185	148	148	243	194	194	280	224	224	311	249	249
5/16" x 6 1/4"	2 3/4	3 3/16	194	156	156	243	194	194	280	224	224	311	249	249
5/16" x 7 1/8"	3 1/2	3 5/16	194	156	156	243	194	194	280	224	224	311	249	249
5/16" x 7 1/8"	4	2 13/16	194	156	156	243	194	194	280	224	224	311	249	249
5/16" x 8 5/8"	5 1/2	2 13/16	194	156	156	243	194	194	280	224	224	311	249	249
5/16" x 9 1/[illegible]"	6	2 3/[illegible]	194	156	156	243	194	194	280	224	224	311	249	249

Reference: ICC-ES Evaluation Report ESR-3179 dated October 2014

Panel Connection at Diaphragm Boundary (Detail C)

Use 5 inch spacing. Loads and screws are the same as used for the design of the panel connection over interior GLB.



Detail C

Diaphragm Chords

Use top and bottom laminations of SLT3 panel at diaphragm edges to function as the diaphragm chord.
Use Chord Width = 27.5 in.

Diaphragm Moment at X = 67.5 ft from Line 1 = $1000(135)^2/8$
= 2,278,125 ft-lb
Diaphragm Moment at X = 31.5 ft from Line 1 = (1000)(31.5)(135.0 – 31.5)/2 = 1,630,125 ft-lbs

Chord Force = M/d
Assume d = [(65.0)(12) – (2)(7.625 wall) – (2)(13.75 wall to center chord)]/12 = 61.44 feet

Strength Level Chord Forces
Chord Force at X = 67.5 ft from end = (2,278,125)/61.44 = 37,079 lbs
Chord Force at X = 31.5 ft from end = (1,630,125)/61.44 = 26,531 lbs

ASD Chord Forces
Chord Force at X = 67.5 ft from end = (0.7)(2,278,125)/61.44 = 25,956 lbs
Chord Force at X = 31.5 ft from end = (0.7)(1,630,125)/61.44 = 18,572 lbs

It is recommended that the chords be designed to be stronger than the shear strength of the diaphragm shear connections. The capacity of the diaphragm is limited by the panel to panel fasteners. Fasteners were required at 4.32 in. spacing but 4.0 in. spacing was provided. Therefore, increase chord forces by (4.32/4.00) = 1.08 when checking chord strength.

TABLE A1.
ALLOWABLE DESIGN PROPERTIES[a,b,c] FOR PRG 320 CLT (for use in the U.S.)

	Major Strength Direction						Minor Strength Direction					
CLT Grades	$F_{b,0}$ (psi)	E_0 (10^6 psi)	$F_{t,0}$ (psi)	$F_{c,0}$ (psi)	$F_{v,0}$ (psi)	$F_{s,0}$ (psi)	$F_{b,90}$ (psi)	E_{90} (10^6 psi)	$F_{t,90}$ (psi)	$F_{c,90}$ (psi)	$F_{v,90}$ (psi)	$F_{s,90}$ (psi)
E1	1,950	1.7	1,375	1,800	135	45	500	1.2	250	650	135	45
E2	1,650	1.5	1,020	1,700	180	60	525	1.4	325	775	180	60
E3	1,200	1.2	600	1,400	110	35	350	0.9	150	475	110	35
E4	1,950	1.7	1,375	1,800	175	55	575	1.4	325	825	175	55
V1	900	1.6	575	1,350	180	60	525	1.4	325	775	180	60
V2	875	1.4	450	1,150	135	45	500	1.2	250	650	135	45
V3	975	1.6	550	1,450	175	55	575	1.4	325	825	175	55

For SI: 1 psi = 0.006895 MPa
(a) See Section 4 for symbols.
(b) Tabulated values are allowable design values and not permitted to be increased for the lumber size adjustment factor in accordance with the NDS. The design values shall be used in conjunction with the section properties provided by the CLT manufacturer based on the actual layup used in manufacturing the CLT panel (see Table A2).
(c) Custom CLT grades that are not listed in this table shall be permitted in accordance with Section 7.2.1

Reference: APA PRG320 Table A1

Tension Capacity

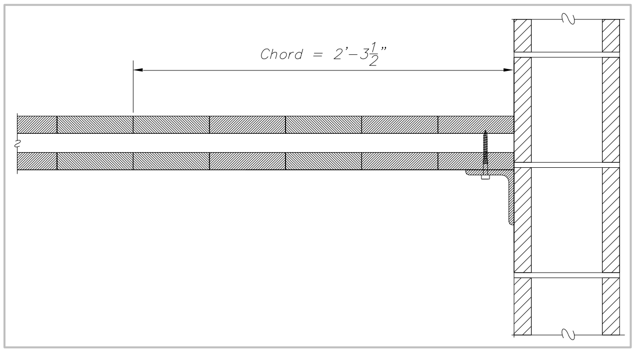
F_{T0} = 450 psi — *APA PRG 320 Table A1 for Grade V2*
C_D = 1.60 — *NDS-2015 Table 2.3.2*

F'_{T0} = (450 psi)(1.6) = 720 psi

$T_{PARALLEL} = F'_{T0}\, A_{PARALLEL}$ — *CLT Handbook, 2013, Chapter 3 Section 2.3 Eqn 9*

$A_{PARALLEL}$ = (2)(1.26)(27.5) = 69.30 in^2 — *Area of layers with fibers running parallel to the direction of the load*

A_{net} = 69.30 – (5 screws)(0.228 shank diameter)
x(3.54 length-0.25 tip) = 65.55 in^2
$T_{PARALLEL}$ = (720)(65.55) = 47,196 lbs > 25,956(1.08) = 28,032 lbs — *NDS-2015 Section 3.8*



Bending

w_{DL} = 10.5 psf self weight + 20 psf DL = 30.5 psf
M_{DL} = -439 ft-lb/ft maximum for 3 – 12' continuous spans
M_{ALLOW} = 1800 ft-lb/ft — *APA PR-L314 Feb 20, 2014*

Bending and Axial Tension

=(1.08)(25,956)/47,421 + 439/(1.6)1800
= 0.591 + 0.152 = 0.743 < 1.0 — *NDS-2015 Eqn 3.9-1 and Section 3.9 Commentary*

Compression

Unbraced length = 144 inch
EI_{eff0} = 79,000,000 lb-in^2/ft
GA_{eff0} = 490,000 lb/ft
F_{C0} = 1150 psi
K_S = 11.5

APA PR-L314 Feb 20, 2014

CLT Handbook, 2013, Chapter 3 Table 2 distributed load pinned ends and NDS-2015 Table 10.4.1.1

$$EI_{app} = \frac{EI_{eff}}{1 + \frac{K_s EI_{eff}}{GA_{eff} L^2}} = \frac{79{,}000{,}000}{1 + \frac{(11.5)(79{,}000{,}000)}{490{,}000(144)^2}}$$

= 72,516,073 lb-in^2/ft

CLT Handbook, 2013, Chapter 3 Eqn 5 and NDS-2015 Section 10.4 and Commentary

$EI_{app\text{-}min}$ = 0.5184EI_{app}

= (0.5184)(72,516,073) = 37,592,332 lb-in^2/ft

CLT Handbook, 2013, Chapter 3 Eqn 8 and NDS 2015 Section 10.4 Commentary

$$P_{cE} = \frac{\pi^2 EI_{app-min}}{l_e^2} = \frac{\pi^2(37{,}592{,}332)}{(144)^2}$$
$$= 17{,}893\ lbs/ft$$

CLT Handbook, 2013, Chapter 3 Section 2.2.2 and NDS-2015 Section 3.7 Commentary

P_c^* = $F_{C0}C_DA$ = (1150)(1.60)(1.26)(2)(12 inch width)
= 55,642 lb/ft

$$C_p = \frac{1 + \left(\frac{P_{cE}}{P_c^*}\right)}{2c} - \sqrt{\left[\frac{1 + \left(\frac{P_{cE}}{P_c^*}\right)}{2c}\right]^2 - \frac{\frac{P_{cE}}{P_c^*}}{c}}$$

$$= \frac{1 + \left(\frac{17{,}893}{55{,}642}\right)}{2(0.90)} - \sqrt{\left[\frac{1 + \left(\frac{17{,}893}{55{,}642}\right)}{2(0.90)}\right]^2 - \frac{\frac{17{,}893}{55642}}{0.90}}$$

$$= 0.3079$$

P_{ALLOW} = $C_PF_{C0}C_DA$

= (0.3079)(1150)(1.60)(1.26)(2)(12 inch width)

= 17,131 lb/ft

P_{ALLOW} Total = (17,131)(27.5/12) = 39,258 lb

P_{cE} = (17,893)(27.5/12) = 41,004 lb

Combined Bending and Compression

$$\left[\frac{P}{P_{allow}}\right]^2 + \frac{M}{M_{allow}\left(1-\frac{P}{P_{cE}}\right)}$$

CLT Handbook, 2013, Chapter 3 Section 2.4 Eqn 10 and NDS-2015 Section 3.9 Commentary

$$= \left[\frac{(25{,}956)(1.08)}{39{,}258}\right]^2 + \frac{439}{(1800)(1.6)\left(1-\frac{(25{,}956)(1.08)}{(41{,}004)}\right)}$$

$$= 0.509 + 0.481 = 0.992$$

Chord Splice at Midspan

Use 5 - PL 1/4x2 ASTM A36 Steel Plates with 12 – 0.315 in. x 3.54 in. long (i.e. 8mm dia x 90 mm long) MiTiCon ASSY 3.0 screws each end spaced at 3.00 in. on center; 0.750 in. steel end distance; 3.50 in. wood end distance; 3/8 in. diameter holes in plate; space plates at 5.50 in.

ϕP_N = (5 each)(0.90)(0.25)(2.0)(36)
= 81.0 kips > (37.079)(1.08) — *AISC 360-10 Eqn D2-1*
= 40.05 kips

ϕP_N = (5 each)(0.75)(0.25)(2.0 – 0.375)(58) — *AISC 360-10 Eqn D2-2*
= 88.36 kips > 40.05 kips

D_r = 0.209 in. (root diameter)
F_{yb} = 150,200 psi — *ICC ESR 3179 Table 1*
ℓ_m = (3.54 in. screw length - 0.25 in. plate thickness)
= 3.29 in.
t_S = 0.25 in.
Z = 293 (Mode IIIs) — *NDS-2015 Section 12.3.1*
C_D = 1.60 — *NDS-2015 Table 2.3.2*
Z' = 293(1.60) = 469 lbs — *NDS-2015 Section 12.3.1*
Allowable Screw Shear = 1320 lbs > 293 lbs — *ICC ESR 3179 Table 1 Steel Shear*

Minimum Spacing = 5d = (5)(8 mm)/25.4 — *ICC ESR 3179 Table 5*
= 1.57 inch < 3.0 inch
Minimum End Distance in Wood = 10d
= (10)(8 mm)/25.4 = 3.15 in. < 3.50 in. — *ICC ESR 3179 Table 5*

L_C = (3.0 – 0.4375) = 2.5625 in. between screws
L_C = (0.75 – 0.4375/2) = 0.531 in. at ends

NOTE: *Check steel bearing at bolt holes. Use diameter 1/16" larger than hole diameter (AISC 360-10 Section B4.3.b)*

Bearing ϕR_N = (0.75)(1.2)(0.531)(0.25)(58) = 6.93 kip — *AISC 360-10 Eqn J3-6a*
Bearing ϕR_N = (0.75)(2.4)(0.228 shank)(0.25)(58) = 5.95 kip

Allowable Force = (5 each)(12 screws)(469 lb/screw)
= 28,140 lbs > (25,956)(1.08) = 28,032 lbs

NOTE: *Z' value from NDS-2015 Section 12.3-1 controls*

Assume screws transfer load from steel plate to upper lamination only and load is transferred from upper lamination to lower lamination. The allowable load transfer between the upper and lower lamination is conservatively limited by the allowable radial tension stress.

F_{vx} = 135 psi — *APA PRG 320 Table A1 for Grade V2*

C_{vr} = 0.72 — *NDS-2015 Section 5.3.10*

$F_{rt} = (1/3)F_{vx}C_{vr} = (1/3)(135)(0.72) = 32.4$ psi — *NDS-2015 Section 5.3.10*

$F'_{rt} = C_D F_{rt} = (1.6)(32.4) = 51.8$ psi

Chord Force = (25,596)(1.08) = 28,032 lbs

Length from end of panel to last screw = 36.5 inch

Allowable load transfer from upper lamination to lower lamination = (51.8 psi)(36.5 length)(27.5 width)
= 51,994 lbs > (0.5)(Chord Force)

Use tension capacity based upon both laminations parallel to load.

NOTE: *For this example, the use of radial tension was judged to be a conservative approach relative to specific values of rolling shear. The force transfer between laminations is shown to be adequate to develop the chord force in the parallel lamination on the bottom of the CLT panel. A similar approach can be taken for panels with a greater number of plys (e.g. 5 or 7 ply panel) or can be accommodated by alternate detailing such as use of greater width of the directly connected layer or use of connections on both top and bottom faces of the CLT panel. Alternately, the CMU wall with reinforcing steel or perimeter support beam can be designed for use as the diaphragm chord.*

Row Tear-Out Capacity

F_{V0} = 135 psi — *APA PRG 320 Table A1 for Grade V2*

F'_{V0} = (135 psi)(1.6) = 216 psi

$$Z'_{RT} = \sum_{i=1}^{n_{row}} n_i F'_V t S_{critital}$$

NDS-2015 Section Appendix E.3

Assume tear-out occurs in upper lamination only

Tear-out Depth in Upper Lam = 1.26 in.

Z_{RT}' = (5 rows)(12 screws)(216 psi)(1.26)(3.00 spacing)
= 48,989 lbs > 28,032 lbs

Group Tear-Out Capacity

Assume only upper lamination is effective

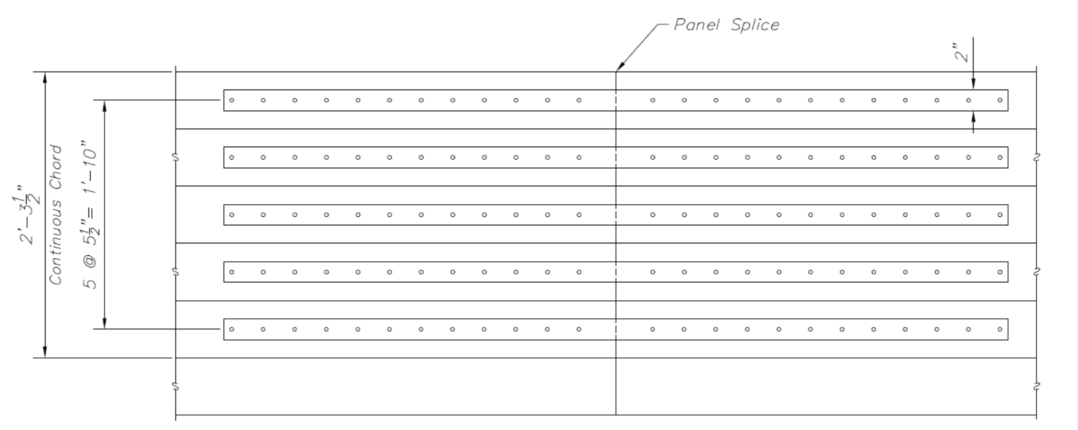
$Z_{GT}' = Z_{RT-1}'/2 + Z_{RT-n}'/2 + F_T'A_{group-net}$ — *NDS-2015 Section Appendix E.4*

$Z_{RT-1}' = Z_{RT-n}'$ = (12 screws)(216 psi)(1.26 thick)(3.00 spacing)
= 9,798 lbs

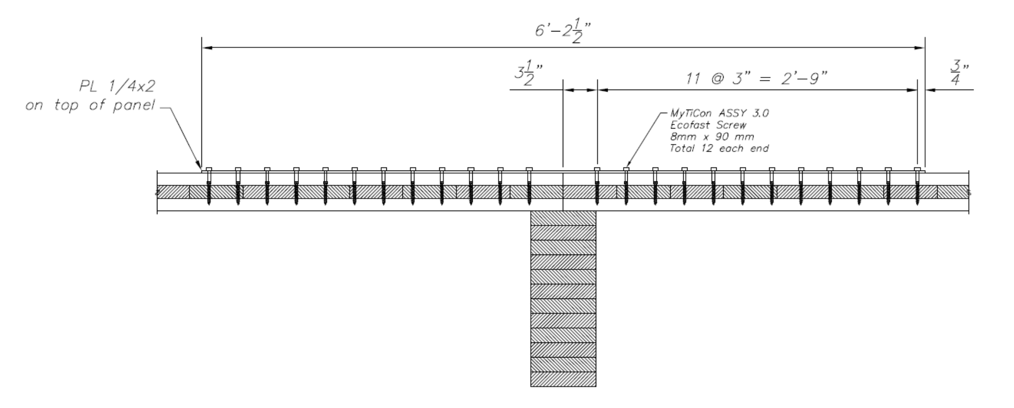
$F_t'A_{group-net}$ = (720 psi)(1 lam)(1.26 thick)(5 rows - 1)
(5.50 row space – 0.228 diameter) = 19,131 lbs

Z_{GT}'= (9,798/2) + (9,798/2) +19,131 = 28,929 lbs > 28,032 lbs

Chord Splice at Midspan (Detail D)



Plan
Chord Splice at Midspan



Section
Chord Splice at Midspan

Chord Splice at X = 31.5 ft from ends

Use 5 - PL 1/4x2 ASTM A36 Steel Plates with 9 - 0.315 in. x 3.54 in. long (i.e. 8mm dia x 90 mm long) MyTiCon ASSY 3.0 screws each end spaced at 3.00 in. on center; 0.750 in. steel end distance; 3.50 in. wood end distance; 3/8 in. diameter holes in plate.

Allowable Force = (5 each)(9 screws)(469 lb/screw) = 21,105 lbs > 18,572(1.08) = 20,058 lbs

Strength Level Diaphragm Seismic Deflection

$$\delta_{dia} = \frac{5vL^3}{8EAW} + \frac{vL}{4G_v t_v} + CLe_n + \frac{\Sigma(x\Delta_c)}{2W}$$

NOTE: *Deflection equation per ANSI/AWC SDPWS-2015 Eqn C4.2.2-1 adapted to account for CLT Panel Size.*

w_{EQ} = 1000 plf
v_{EQ} = 67,500/61.44 = 1099 plf

Deflection Due to Bending

$\delta = 5vL^3/8EAW$

A = (2 laminations)(1.26)(27.5) = 69.30 in^2

E = 1,400,000 psi

$\delta = (5)(1099)(135)^3/(8)(1,400,000)(69.30)(61.44) = 0.284$ in.

Deflection Due to Shear

$\delta = vL/4G_vt_v$

$v = wL/2B$ where B = diaphragm width

$t_v = A/B$ where A = area of diaphragm

$\delta = wL^2/8AG$ by substitution, deflection due to shear can be expressed in terms of apparent shear stiffness GA.

NOTE: *The in-plane shear stiffness of the CLT panels has not yet been tested by Structurlam, but tests on other CLT panels have resulted in proposed equations to estimate the stiffness.*

$$G_{eff,CA} = \frac{Kb^2 n_{CA} m^2}{5t_{gross}(m^2+1)}$$

$$G_{eff,CLT} = \left(\frac{1}{G_{lam}} + \frac{1}{G_{eff,CA}}\right)^{-1}$$

NOTE: *Equations for shear stiffness G_{eff} are in accordance with Flaig M., Blaß H. J.: Shear strength and shear stiffness of CLT-beams loaded in plane. In: Proceedings. CIB-W18 Meeting 46, Vancouver, Canada, 2013, Paper 46-12-3.*

K = slip modulus of crossing areas

b = width of lamelle

m = number of longitudinal lamellae

n_{CA} = number of glue lines within element thickness

t_{gross} = 3.90 inch for SLT3

$G_{lam} = E_0/16$ = 1,400,000/16 = 87,500 psi

Use K = 4.0 N/mm^3 = 14735 lb/in3

Use b = 5.50 in.

Use m = 17 for 96 in. panel width

Use n_{CA} = 2 for SLT3

APA PRG 320-2012 for Grade V2

$$G_{eff,CA} = \frac{(14735)(5.50)^2(2)(17)^2}{5(3.90)(17^2+1)} = 45{,}559\ psi$$

$$G_{eff,CLT} = \left(\frac{1}{87{,}500} + \frac{1}{45{,}559}\right)^{-1} = 29{,}960\ psi$$

Recommended G_{eff}

Panel	STL3	SLT5	SLT7	SLT9
G_{eff}	30,000 psi	33,000 psi	34,000 psi	35,000 psi

GA = (30,000)(3.90)(12) = 1,404,000 lbs/ft

δ = (1000 lb/ft)(135 ft)^2(12 in/ft)/(8)(1,404,000 lb/ft)(65 ft)

= 0.300 inch

Deflection Due to Fastener Slip at Panel to Panel Joints

$\delta = CLe_n$

The C term for deflection due to fastener slip in a CLT diaphragm is based on the derivation approach given in Appendix Section A4.1.4 of *Applied Technology Council, Guidelines for the Design of Horizontal Wood Diaphragms, September 1981.* For the case of uniformly loaded CLT diaphragm, the contribution of fastener slip to diaphragm deflection varies by Panel Length, $P_{L,}$ and Panel Width, $P_{W,}$ as follows:

$$C = \frac{\frac{1}{P_L} + \frac{1}{P_W}}{2} = \frac{\frac{1}{36} + \frac{1}{8}}{2} = 0.076$$

NOTE: *Fastener slip contribution is based on the primary panel size used to compose the overall diaphragm dimensions. Based on inspection of the C term, the effect of the smaller length panels (i.e. 31.5') on nail slip contribution to deflection for this example is less than 5%.*

Recommended C term

Panel Size WxL	8'x12'	8'x16'	8'x24'	8'x32'	8'x36'	8'x40'
C	0.104	0.094	0.083	0.078	0.076	0.075

Load Slip Modulus = γ = (180,000/2) $D^{1.5}$

γ = 90,000 $(0.209)^{1.5}$ = 8,600 lb/in.

Fastener Force = (1038 lb/ft)/(3 screws/ft) = 346 lb/screw

e = 346/8,600 = 0.040 in.

δ = (0.076)(135)(0.040) = 0.410 in.

NDS-2015 Section 10.3.6

NOTE: *Reference #188 in NDS C11.3.6 (Zahn, J. J., Design Equation for Multiple-Fastener Wood Connections, Madison, WI, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1991) indicates that half of the NDS slip modulus is an appropriate value for bearing perpendicular to the grain. For this example, half the load slip modulus is used to account for possible influence of perpendicular crossing layers.*

Deflection Due to Chord Splice Slip

Load Slip Modulus = γ = (270,000/2) $D^{1.5}$

γ = 135,000 $(0.209)^{1.5}$ = 12,899 lb/in.

Δ_C = 2(T or C)/γ n = (2)(37,079)/(12,899)(60) = 0.096 in.
at midspan

Δ_C = 2(T or C)/γ n = (2)(26,531)/(12,899)(45) = 0.091 in.
at x = 31.5 ft

$\Sigma(x\Delta_C)/2W$ = [(31.5)(0.091) + 67.5(0.096) +
(31.5)(0.091)]/2(61.44) = 0.099 in.

Assume slip on compression chord = slip on tension chord

δ = (0.099)(2) = 0.198 in.

NDS-2015 Section 10.3.6

NOTE: *For this example, half of the load slip modulus is used to account for possible influence of perpendicular crossing layers.*

Total Diaphragm Deflection

Total Deflection = 0.284 + 0.300 + 0.410 + 0.198
= 1.192 in. using NDS estimate of fastener slip.

MyTiCon Test Results

For screws spaced 4" oc

Strength Level Force = (1038)(4)/12 = 346 lbs/screw

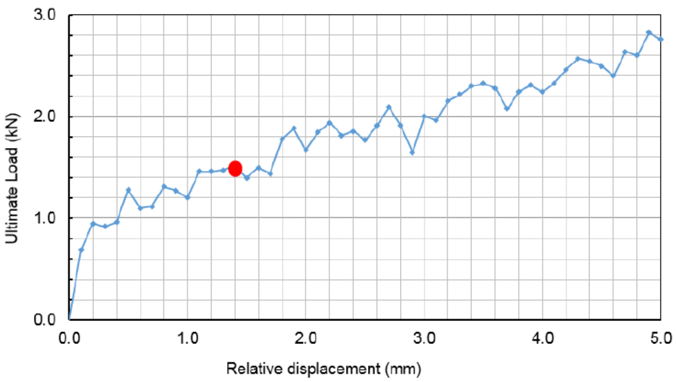
Force = (346 lb)(0.004448 kN/lb) = 1.54 kN/screw

The MyTiCon average test results shown below indicate a wood displacement = 1.4 mm (0.055 in.) corresponding to 1.5 kN force per screw.

e_n = 0.055 in.

δ = (0.076)(135)(0.055) = 0.566 in.

Total Displacement = 0.284 + 0.300 + 0.566 + 0.198
= 1.348 in. using test values for fastener slip.



Verify Flexible Diaphragm Assumption

ASCE 7-10 Section 12.3.1.3 permits diaphragms to be idealized as flexible where the computed maximum in-plane deflection of the diaphragm under lateral load is more than two times the average story drift of adjoining vertical elements of the seismic force-resisting system of the associated story under equivalent tributary lateral load.

The average story drift in the north-south direction for the CMU walls was computed in accordance with ASCE 7-10 Section 12.8.6 as $\Delta = \delta_x = 0.10$ in.

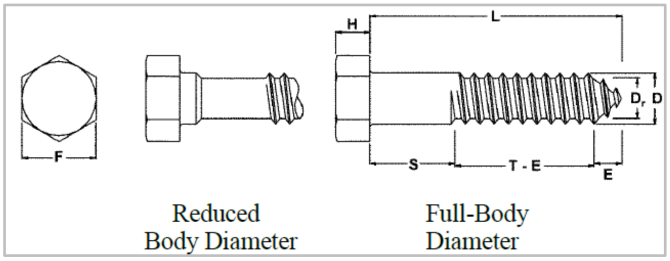
Diaphragm Deflection = 1.192 > 2Δ = (2)(0.10) = 0.20

The diaphragm can be assumed to be flexible.

NOTE: *For this example, diaphragm deflection is compared to the average story drift of adjoining shear walls and the original assumption of flexible is verified. While distribution of forces to vertical elements based on semi-rigid diaphragm analysis is not undertaken in this example, the method of calculation of the diaphragm deflection can be used to establish diaphragm stiffness for semi-rigid diaphragm analysis. A generally acceptable alternative to semi-rigid diaphragm analysis is the envelope analysis where distribution of horizontal diaphragm shear to each vertical resisting element is the larger of the shear forces resulting from analyses where the diaphragm is idealized as flexible and the diaphragm is idealized as rigid.*

Alternative Lag Screw Connections

Standard lag screws per ANSI/ASME Standard B18.6.1 could be used in lieu of nails or proprietary self-tapping screws. Lead holes are required in accordance with NDS-2015 Section 12.1.4. 5/16" diameter lag screws are used for this alternative. The shear capacity is based on lag screws that are assumed to be "reduced body diameter" or have threads located in the shear plane.



Detail	Description	Lag Screw (D x L), inch	Shear Capacity C_D=1.0 (lbs)	Failure Mode	Demand	Required Spacing/No
A	Panel to Panel Connection	5/16x3.50	137.8	IIIs	727 plf	3.6 inch
B	Panel Splice over GLB	5/16x7.0	128.6	IV	727 plf	3.4 inch
C	Panel Connection at Diaphragm Boundary	5/16x7.0	128.6	IV	727 plf	3.4 inch
D	Chord Splice at Midspan	5/16x3.50	248.4	IV	28,032 lbs	15 lags each end each plate