Cross-Laminated Timber Diaphragms

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Cross-Laminated Timber (CLT) panels are becoming increasingly common as a roof or floor deck system in mass timber buildings. The roof and floor deck systems need to be carefully engineered and detailed to serve as diaphragms resisting wind and seismic loads. The diaphragm transmits lateral loads to the vertical lateral load resisting elements – usually shear walls or braced frames.

Figure 1. Longitudinal side joint.

It is common for CLT floor decks to have a concrete topping slab for sound isolation. The concrete topping slab can be detailed to serve as the lateral load resisting diaphragm, but it is often more practical to engineer the CLT deck to serve as the diaphragm. The American Wood Council's (AWC) 2021 *Special Design Provisions for Wind & Seismic* (SDPWS), referenced in the 2021 *International Building Code* (IBC), contains CLT diaphragm design provisions.

Diaphragm Flexibility

In most instances, it is reasonable to consider CLT floor and roof decks to act as rigid diaphragms with lateral loads distributed to the vertical resisting elements based on their relative stiffness. It is recommended that the aspect ratio (L/W) of the rigid diaphragm not exceed 3:1 if there is a non-composite concrete topping (2½-inch minimum thickness) or 2:1 if there is no concrete topping. If the aspect ratio exceeds these limits but is not more than 4:1, the diaphragm may be modeled as semi-rigid.

Alternatively, rather than performing a semi-rigid diaphragm analysis, which can be tedious, the lateral analysis may be run twice – once assuming a rigid diaphragm and once assuming a flexible diaphragm, and designing for the envelope of the two. If the lateral force-resisting elements are similar in stiffness and well distributed throughout the footprint, the two solutions will often not be far apart.

The CLT decks can be considered flexible diaphragms only if calculations demonstrate that the diaphragm's in-plane deflection is more than twice the average drift of the vertical resisting elements. This is outlined in the American Society of Civil Engineers' ASCE/SEI 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, Section 12.3.1.3. In no case should the diaphragm aspect ratio exceed 4:1.

Diaphragm Strength

CLT shear values are based on ANSI/APA PRG-320, *Standard for Performance-Rated Cross-Laminated Timber*. V (in-plane shear strength) = t (thickness of cross plies) × 12" × F_v × 1.6 (CD) / 1.5.
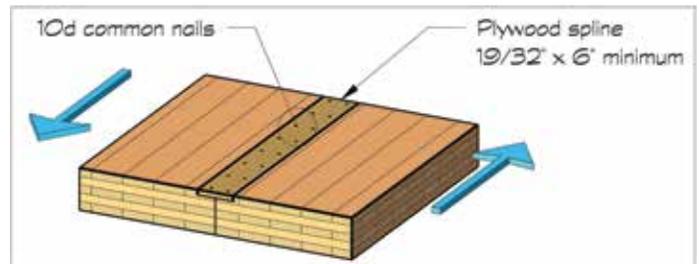
The in-plane shear strength of a CLT panel is controlled by the shear strength of the transverse cross laminations. The allowable in-plane shear values are shown in *Table 1*. Per 2021 SDPWS, CLT panels should be designed to resist 2.0 times the induced shear associated with seismic loads to preclude a non-ductile shear rupture.

The in-plane shear strength of a CLT deck is typically limited by the strength of connections between panels and connections at boundary elements rather than by the strength of the CLT panels. Consequently, careful detailing of the panel connections and fasteners is crucial.

CLT Connections

Longitudinal side joints between CLT panels are most commonly achieved with plywood splines fastened with common nails. Spline joints deform and dissipate energy during a seismic event, lending ductility to the diaphragm. If thicker splines are used or fastened with screws rather than common nails, some ductility is sacrificed.

Table 1. CLT in-plane shear ASD reference design values (lbf/ft of width).

CLT Layup	F_v (psi)	4⅛" (3-ply)	6⅞" (5-ply)	9⅝" (7-ply)
E1	135	2385	4769	7154
E2	180	3180	6359	9539
E3	110	1943	3886	5829
E4	175	3091	6182	9274
E5	150	2650	5299	7949
V1	180	3180	6359	9539
V2	135	2385	4769	7154
V3	175	3091	6182	9274
V4	135	2385	4769	7154
V5	150	2650	5299	7949
CLT Layup	F_v (psi)	4½" (3-ply)	7½" (5-ply)	10½" (7-ply)
S1	130	2496	4992	7488
S2	150	2880	5760	8640
S3	115	2208	4416	6624

The allowable unit shear capacity for plywood splines are shown in *Table 2*.

Some dynamic testing of spline joints with screw fasteners has been done at the University of British Columbia. The research suggests that spline joints with inclined screws loaded axially typically exhibit high initial stiffness and ultimate static capacity but are prone to non-ductile failure. Spline joints with screws installed at 90 degrees and loaded in shear exhibited lower initial stiffness and ultimate static capacity but failed in a more ductile fashion.

Transverse end joints between CLT panels must resist the same in-plane shear as the longitudinal joints. In most instances, the ends of the CLT panels are supported on a glulam timber beam, and the shear is transmitted through the beam with timber screws.

Diaphragm boundary elements (chords and collectors) are often glulam timber beams. Connections at the ends of timbers serving as boundary elements must be detailed to resist the axial forces induced into them to maintain the continuity of the chords. If the chord forces must be resisted by the CLT panels rather than by timber beams, steel straps are needed at the panel joints. Per 2021 SDPWS, chord splices should also be designed to resist 2.0 times the induced seismic chord force to preclude non-ductile behavior. The timber screws fastening the CLT panels to the boundary timbers need to be spaced to transmit the chord and collector forces.

The allowable shear capacity of timber screws fastening CLT panels to timber beams is shown in *Table 3*. The values in *Table 3* are based on timber screws with a minimum F_{yb} of 136.6 ksi, a CLT specific gravity of 0.42, and a timber beam specific gravity of 0.49. The load is assumed to be applied parallel to the grain of the timber beam. These values have been increased for a load duration factor, C_D, of 1.6 and a diaphragm adjustment factor, C_{di}, of 1.1

The timber screw values contained in *Table 3* are controlled by Mode IV fastener yielding in accordance with AWC's *National Design Specification® for Wood Construction* 12.3.1 as required by 2021 SDPWS.

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Table 2. Allowable unit shear capacity of splines (lbf/ft).

Spline Thickness	10d 6"o.c.	10d 4"o.c.	10d 2½"o.c.	2 rows 10d 4"o.c.	2 rows 10d 2½" o.c.
Wind					
$^{19}/_{32}$"	505	672	1007		
$^{23}/_{32}$"				995	1427
Seismic					
$^{19}/_{32}$"	360	480	720		
$^{23}/_{32}$"				710	1020

Source: 2021 SDPWS Tables 4.2A and 4.2B based on "Sheathing" grade wood structural panels and a 3-inch nominal nailing face.

Table 3. Allowable shear capacity of timber screws in CLTs (lbf).

Thickness	Fastener Diameter	Fastener Length	Major Strength Direction	Minor Strength Direction
4⅛ "	¼" (6mm)	7⅞" (200mm)	348	348
4⅛"	$^{5}/_{16}$" (8mm)	7⅞" (200mm)	456	364
6⅞"	$^{5}/_{16}$" (8mm)	11⅞" (300mm)	456	364
6⅞"	⅜" (10mm)	11⅞" (300mm)	669	480
9⅝"	⅜" (10mm)	15" (380mm)	669	480
9⅝"	½" (12mm)	15¾" (400mm)	961	676

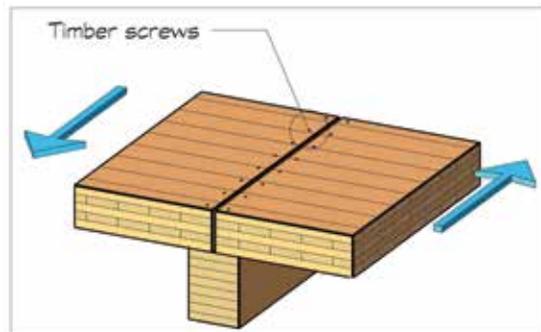Source: Heavy & Mass Timber Connections Handbook – MyTiCon.

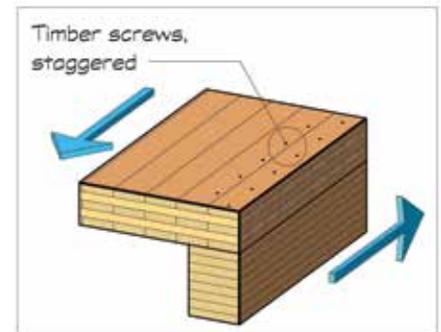Figure 2. Transverse end joint.

Figure 3. Diaphragm boundary.

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