



CLT Diaphragm Design for Wind and Seismic Resistance

Using SDPWS 2021 and ASCE 7-22

Cross-laminated timber (CLT) has become increasingly prominent in building construction and can be seen in buildings throughout the world. Specifically, the use of CLT floor and roof panels as a primary gravity force-resisting component has become relatively commonplace. Now, with availability of the 2021 *Special Design Provisions for Wind and Seismic* (SDPWS 2021) from the American Wood Council (AWC), U.S. designers have a standardized path to utilize CLT floor and roof panels as a structural diaphragm. Prior to publication of this document, projects typically had to receive approval to use CLT as a structural diaphragm on a case-by-case basis from the local Authority Having Jurisdiction (AHJ).

This paper highlights important provisions of SDPWS 2021 for CLT diaphragm design and recommendations developed by the authors in the more extensive *CLT Diaphragm Design Guide*, based on SDPWS 2021, published by WoodWorks – Wood Products Council.

AWC SDPWS 2021

SDPWS 2021 is the first edition to provide direct provisions for CLT to be used as an element in a diaphragm or shear wall. To differentiate between CLT and light-frame lateral force-resisting systems, it adopts the terminology *sheathed wood-frame* for light-frame diaphragms (SDPWS §4.2) and shear walls (SDPWS §4.3), and includes new sections for CLT diaphragms (SDPWS §4.5) and shear walls (SDPWS §4.6). SDPWS 2021 is referenced in the 2021 International Building Code (IBC).

Shear Capacity

SDPWS 2021 has a single nominal shear capacity for each set of construction details, v_n , defined in §4.1.4 for use with both wind and seismic design. From this nominal shear capacity, the Allowable Stress Design (ASD) and Load and Resistance Factor Design (LRFD) wind and seismic design capacities are determined by dividing by the ASD reduction factor, Ω_D , or multiplying by a resistance factor, ϕ_D , for LRFD design as summarized in Table 1. For sheathed wood-frame diaphragms, the SDPWS

Photo: KPFF



MGA | Michael Green Architects / Kattera / KPFF

Catalyst in Spokane Washington

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provides nominal shear capacities in tables for prescribed details—such as Table 4.2A for common blocked wood structural panel diaphragms. The nominal capacity tables for sheathed wood-frame systems in SDPWS 2021 differ from earlier editions by providing a single nominal value for each specific construction assembly. Prior editions provided different wind and seismic nominal values. For CLT diaphragms, SDPWS 2021 does not provide prescribed details. Rather, the nominal diaphragm shear capacities are based on engineering calculations.

TABLE 1: SDPWS 2021 design capacity

Loading	ASD Design Capacity v_n / Ω_D	LRFD Design Capacity $\phi_D v_n$
Seismic	$v_n / 2.8$	$0.50 v_n$
Wind	$v_n / 2.0$	$0.80 v_n$

CLT Diaphragm Provisions

SDPWS 2021 §4.5 contains new provisions for the design of CLT diaphragms. When using these provisions, an engineered approach is followed to develop details that meet the required design loads defined by the building code (IBC) and ASCE 7. This is unlike wood structural panel sheathed wood-frame diaphragms, which have prescribed construction details and associated tabular nominal unit shear capacities.

When designing CLT diaphragms, the general requirements for all wood systems in SDPWS §4.1 apply, including limits on when wood members can be used to resist seismic forces from concrete or masonry walls in §4.1.5. However, the requirements specific to sheathed wood-frame diaphragms in SDPWS §4.2 do not apply, including diaphragm aspect ratio limits (§4.2.2), deflection equations (§4.2.3), requirements on structures with torsional irregularities (§4.2.5), and requirements on cantilever diaphragms (§4.2.6).

Photo: Marcus Kauffman



Panel-to-panel connections with splines at The Canyons in Portland, OR

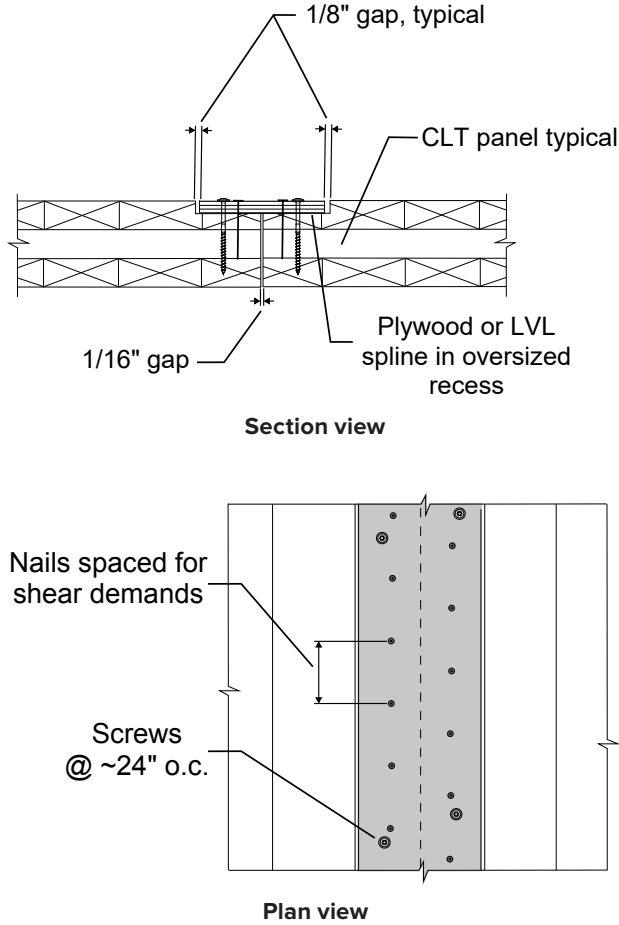


FIGURE 1: Example CLT diaphragm panel-to-panel connection with a spline

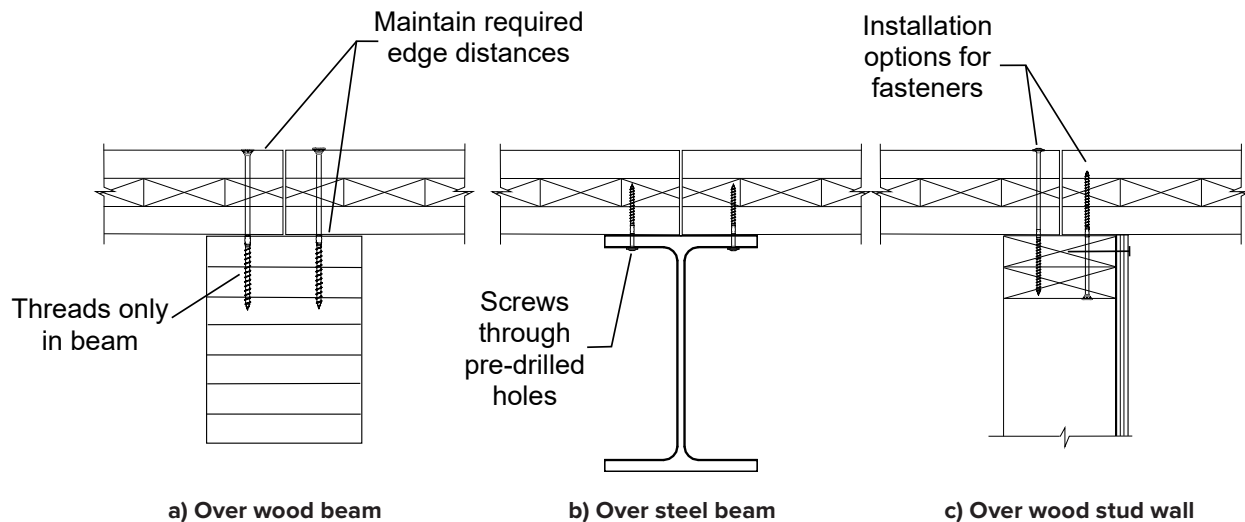


FIGURE 2: Example CLT diaphragm panel-to-panel connections over framing below

SDPWS §4.5.4 Item 1 requires that *diaphragm shear forces* be transferred between adjoining CLT panels and between CLT panels and boundary elements through dowel-type fasteners in shear. Dowel-type fasteners include nails, wood screws, lag screws, and bolts. Dowel-type fasteners in shear are installed perpendicular to the shear plane and not used in tension (withdrawal) or compression to resist diaphragm shear. In practice, nails and proprietary self-tapping screws are mostly commonly used in CLT diaphragm connections. SDPWS §4.5.4 Item 2 does not permit the use of shear connections to transfer the diaphragm tension forces, such as at chords and collectors. Example diaphragm shear connections are shown in Figure 1 and Figure 2.

For diaphragm shear connections, the capacities of the dowel-type fasteners (nails and screws) in shear, Z , are calculated using the yield mode equations of the National Design Specification® (NDS®) for Wood Construction §12.3.1. Mode III_s or Mode IV of this section is required to control the capacity of the diaphragm shear connections. The nominal diaphragm shear capacity of the connection is based on an adjusted design capacity, Z^* , defined in SDPWS §4.5.4 Item 1. Z^* is similar to the adjusted design capacity, Z' , in NDS Table 11.3.1 except the ASD and LRFD-specific adjustment factors, C_D , K_F , ϕ , and λ , are not applied.

$$Z^* = Z \times C_M \times C_t \times C_g \times C_{\Delta} \times C_{eg} \times C_{di} \times C_{tn}$$

The nominal shear capacity per fastener is:

$$V_n = 4.5 Z^*$$

Fasteners in such connections are often specified at a regular on-center spacing, s , in inches. The nominal unit diaphragm shear capacity (plf) of such a connection is calculated as:

$$v_n = 4.5 Z^* (12 \text{ in/ft}) / s$$

The requirements and calculation method apply to the connections transferring diaphragm shear, including panel-to-panel, panel-to-chord, and panel-to-collector connections. Figure 3 shows an example of a CLT diaphragm with components and connections labeled for discussion. CLT diaphragm design is commonly approached using a deep beam analogy, where chords are assumed to resist all the flexural forces and the diaphragm deck is assumed to resist a uniform shear stress over the depth of the diaphragm. The diaphragm shear connections shown include (a) panel-to-panel connections not over framing, (b) panel-to-panel connections over a beam, (c) panel-to-collector connections, and (d) panel-to-chord connections. Each connection type in the system can have unique calculated diaphragm shear capacities. If a spline connection is used at the panel-to-panel connection perpendicular to the supports (see “a” in Figure 3), and long screws through the panel to the beam below are used at the ends of the panels (see “b” in Figure 3), these two details are very unlikely to have equal capacities. It is appropriate to consider the diaphragm shear capacities of connections relative to their demands. If a single diaphragm capacity for the whole system is useful, this capacity can be found as the shear demand corresponding to the limiting connection in the diaphragm system.

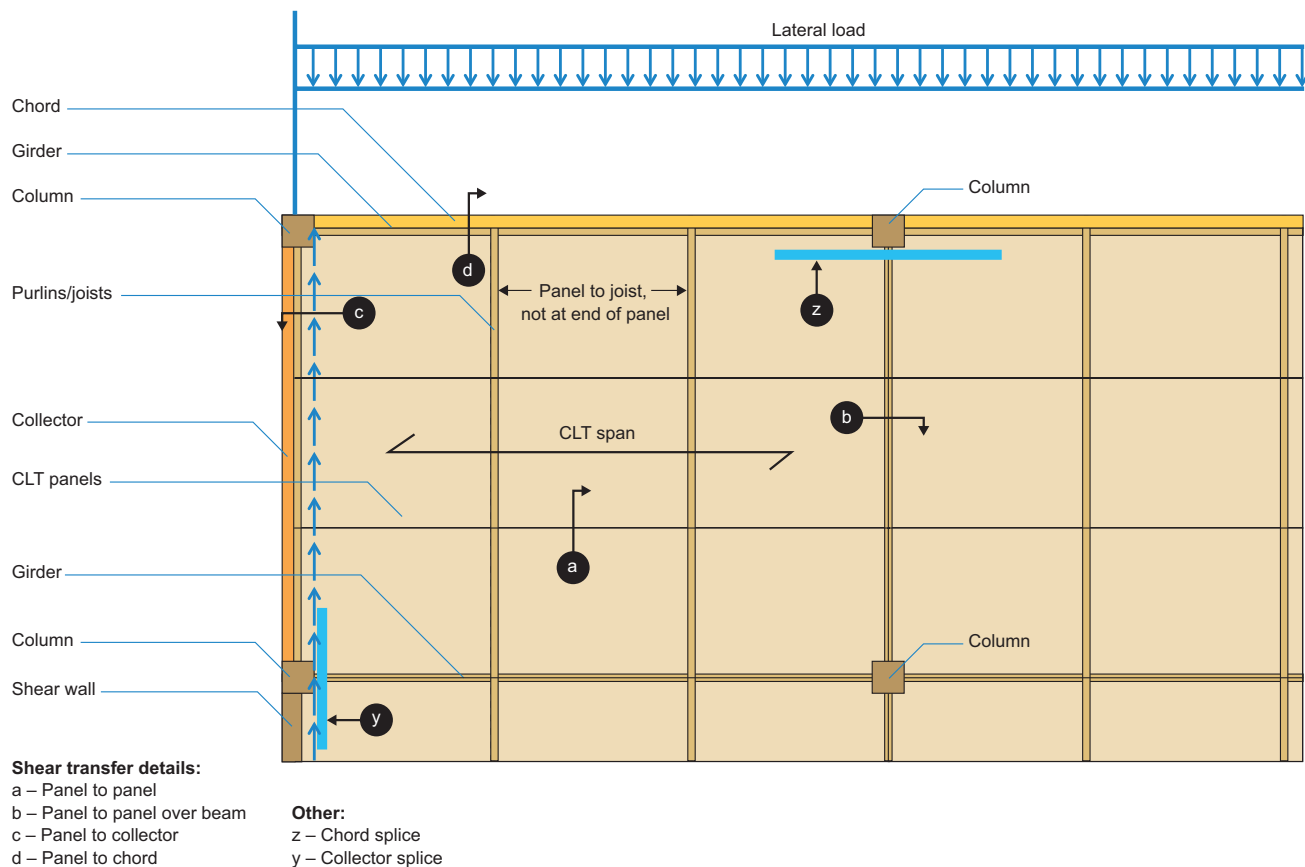


FIGURE 3: Typical CLT diaphragm components and connections

The chords, collectors and their connections, (y) and (z), and other structural components transferring shear, such as the CLT panels themselves, have different design requirements. The connections of chords and collectors are not required to use dowel-type fasteners in shear controlled by yield modes III_s or IV. However, chords, collectors, and their connections must be designed to higher required capacity with a force increase factor applied to the diaphragm design force. The required force increase factors are found in SDPWS §4.5.4 Item 3, including Exceptions 1 and 2, and summarized in Table 2.

The capacities of these diaphragm components are calculated using the provisions of the applicable material design method. The design capacities of wood chords, collectors, and their connections are calculated using the NDS, and not using the SDPWS nominal capacity (4.5 Z*) and reduction factors.

TABLE 2: Force increase factors for CLT diaphragm components

Component	Force Increase Factor γ_D	
	Seismic	Wind
Chord splice connections between wood elements where the connection is using fasteners in shear controlled by yield mode III _s or IV	1.5	1.0
Wood elements and connections between wood elements not meeting the above	2.0	1.5
Steel elements including connections between steel elements	2.0	2.0

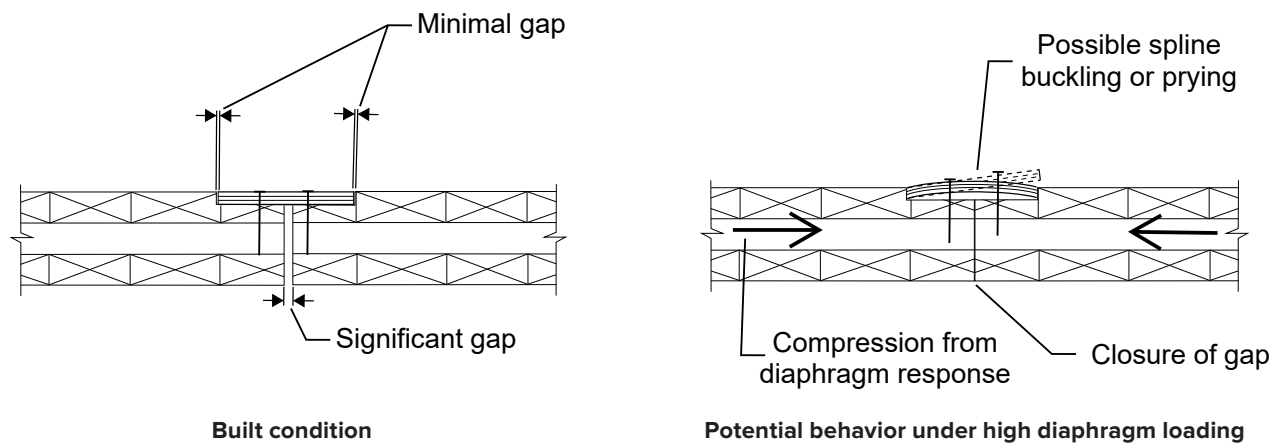


FIGURE 4: Example of inappropriate detail with significant gap

Important Detailing Considerations

CLT or Framing as Boundary Element

Boundary elements for diaphragms include chords, collectors, their splices, and their connections to the vertical lateral force-resisting system (VLFRS). While the requirements for chords and collectors can vary, the detailing is often similar. In many cases, a structural component acts as a collector for loading in one direction and as a chord element for loading in the orthogonal direction.

Boundary elements in CLT diaphragms can include steel straps, framing components supporting the CLT such as steel or timber beams, or the CLT panels themselves. When CLT diaphragms are supported by light-frame walls, the top plates of the walls below can act as chord and collector elements.

In practice, it is often advantageous to use CLT panels, coupled with top side metal straps at panel breaks, as the primary chord and collector elements. This is especially true for glulam-supported floor systems, as it can be challenging to transfer chord/collector demands across some beam-to-column connections.

Connection Gaps and Tolerances

The details shown in Figure 1 and Figure 2 may be constructed with measurable gaps between the panels. These gaps may be a result of fabrication tolerances, intentional under-sizing of the panels for ease of construction, or placement inaccuracies. When panels meet over framing as shown in Figure 2 and the framing functions as a shear transfer component between the panels, gaps are of little consequence to the diaphragm shear behavior. If the CLT panels are acting as a boundary

element and panel-to-panel bearing is used to transfer compressive axial forces at the ends of the panels, the presence of gaps must be accounted for in design and excessive gaps need to be filled with a non-compressible material in the boundary element region to provide an axial load path.

Where a recessed spline is used to transfer diaphragm shear forces between CLT panels, as seen in Figure 1, there are two types of gaps—gaps between CLT panels, and gaps between the shoulders of the recess in the CLT panel and the spline placed in the recess. Under design-level loading events, CLT panels in diaphragms mostly behave as rigid elements; however, they can shift in response to applied forces, creating deformations at the panel-to-panel connections. Panels near the compression boundary are pushed closer together, while panels near the tension boundary are pulled apart. Panels in shear rotate slightly and shift in response to the shear stresses. At areas of local compression between panels, if the compression is resisted by the spline as shown in Figure 4, it may create a prying or buckling reaction in the spline, which may reduce the shear capacity of the spline connection.

To mitigate this behavior, it is recommended that, in spline connections, the gap between panels be not more than the sum of the gaps on each side of the spline. This allows the panel gap to close and achieve bearing before the spline side member gaps close completely. To follow this recommendation, specify that the width of the recess in the CLT panels be larger than the specified width of the spline material. A convenient set of dimensions is 5-7/8-in.-wide plywood spline with a 1/8-in. gap on each side, and a nominal gap of 1/16 in. between panels with a 1/8-in. maximum gap allowed.

Design Loads and Force Increase Factors

The SDPWS CLT diaphragm design method requires designing the diaphragm shear connections to the *diaphragm design forces* specified by the building code, labeled here as F_{design} . The 2021 IBC references ASCE 7-16 for derivation of the appropriate wind and seismic diaphragm design forces and requirements. Following the SDPWS, the remaining components of the diaphragm are designed to increased diaphragm design forces, $\gamma_D F_{design}$.

The intent of the SDPWS force increase factors as described in the SDPWS Commentary is to “target diaphragm shear strengths with a minimum margin above the ASD design level of [2.0 for wind and] 2.8 for seismic.” In other words, if a CLT diaphragm system is designed perfectly to the SDPWS 2021 requirements with all components having ASD capacities exactly equal to their required ASD seismic design forces, the diaphragm system strength is expected to be at least 2.8 times the ASD *diaphragm design force*.

A common question regarding CLT diaphragm design is how the SDPWS force increase factors should be used in conjunction with various amplification factors of ASCE 7 for seismic design. The following is the assessment of the authors on how to combine the SDPWS force increase factors and various ASCE 7 seismic force amplification factors.

For seismic design, the *diaphragm design force* is calculated following ASCE 7-16 §12.10.1.1 which can be described in equation form as:

$$F_{design} = \max(F_{px}, F_x) + \Omega_0 F_{x_transfer}$$

where F_{px} is the inertial diaphragm design force calculated using ASCE 7-16 Eq. 12.10-1 through 12.10-3, F_x is the force in the diaphragm from the structural analysis of the seismic lateral force-resisting system, and $F_{x_transfer}$ is the transfer force through the diaphragm, when applicable, from one vertical force-resisting component to another. These diaphragm transfer forces occur at out-of-plane offset irregularities of the vertical components, such as horizontal structural irregularity Type 4 of ASCE 7-16 Table 12.3-1.

Following common practice as presented in the Structural Engineers Association of California *Structural/Seismic Design Manual Vol 1*, the redundancy factor, ρ , of ASCE 7 is equal to 1.0 for determination of the non-transfer design forces on the diaphragm. Therefore $\rho > 1.0$ is not included in the *diaphragm design force*, F_{design} .

Where a significant seismic diaphragm transfer force, $F_{x_transfer}$, occurs, ASCE 7-16 §12.10.1 can require the application of the vertical seismic force-resisting system overstrength factor, Ω_0 , to the seismic transfer forces within the *diaphragm design force*. In this case, the overstrength factor, Ω_0 , is within F_{design} for the diaphragm design and thus cumulative with the SDPWS force increase factor γ_D :

$$\gamma_D F_{design} = \gamma_D \max(F_{px}, F_x) + \gamma_D \Omega_0 F_{x_transfer}$$

For structures in Seismic Design Categories C through F, the required design forces for collectors potentially include amplification by Ω_0 per ASCE 7-16 §12.10.2. If the structure is entirely braced by light-frame wood shear walls, the exception to §12.10.2 applies and Ω_0 is not applicable to the collector design. Otherwise, the collector, collector splice connections, and collector connections to the VLFPS must be designed to the maximum of the three enumerated force levels in §12.10.2 and the increased diaphragm design forces required by SDPWS 2021, shown in Table 3. As the load increase factor in SDPWS 4.5.1 Item 3 applies to the *diaphragm design forces*, the amplification of forces by Ω_0 per ASCE 7-16 §12.10.2 for collector design is not cumulative with the load increase factor, γ_D , of the SDPWS. This is different than amplification of diaphragm transfer forces by Ω_0 per ASCE 7-16 §12.10.1 as the transfer forces are part of the diaphragm design forces.

TABLE 3: Design force requirements for collectors, collector splices, and connections to VLFPS

Source of Design Force	Required Design Force*
SDPWS 2021 requirement for all collectors	
SDPWS load increase	$\gamma_D \max(F_{px}, F_x) + \gamma_D \Omega_0 F_{x_transfer}$
ASCE 7-16 §12.10.2.1 SDC C through F, when not entirely braced by wood light-frame shear walls	
7-16 12.10.2.1 Item 1	$\Omega_0 F_x + \Omega_0 F_{x_transfer}$
7-16 12.10.2.1 Item 2	$\Omega_0 F_{px,eq\ 12.10-1} + \Omega_0 F_{x_transfer}$
7-16 12.10.2.1 Item 3	$F_{px,eq\ 12.10-2} + \Omega_0 F_{x_transfer}$

*Use the maximum of applicable forces

For structures in Seismic Design Categories D, E, and F with certain structural irregularities, the design forces for collectors and connections between the diaphragm and vertical elements may need to be increased by 25% per ASCE 7-16 §12.3.3.4. Similar to the Ω_o of §12.10.2, this is an increase in the required strength of specific components and not an increase in the diaphragm design force, and not included in F_{design} . For collectors, collector splices, and connections to the VLFRS, γ_D is 2.0 for seismic design. Therefore, the design force, $\gamma_D F_{design}$, required by SDPWS will always be greater than $1.25 F_{design}$ when required by ASCE 7. For the CLT diaphragm shear connections from the CLT panels directly to the collectors and VLFRS, γ_D does not apply in the SDPWS; therefore, these shear connections will need to be designed to $1.25 F_{design}$ if triggered in ASCE 7-16 §12.3.3.4.

Diaphragm Flexibility

In ASCE 7, several specific diaphragm types can qualify prescriptively as flexible or rigid. CLT diaphragms are not included in the prescriptive categories. ASCE 7 does allow a diaphragm to be idealized as flexible when:

$$\frac{\delta_{MDD}}{\Delta_{ADVE}} > 2$$

where δ_{MDD} is the maximum in-plane diaphragm deflection; Δ_{ADVE} is the average deflection of adjoining vertical elements of the VLFRS. ASCE 7 does not provide a method to idealize a diaphragm as rigid by analysis; however, this approach is addressed in IBC §1604.4, and SDPWS §4.1.7. These approaches typically require the calculation of diaphragm deflections. Given the large size and high in-plane stiffness of CLT panels, it is usually the case that CLT diaphragms can be idealized as rigid if used with wood structural panel shear walls or moment frames. When CLT diaphragms are used with concrete shear walls or braced frames, sometimes the diaphragms can be idealized as rigid and sometimes as flexible. Alternative options include a semi-rigid or envelope analysis.

Methods to calculate the CLT diaphragm deflection, including hand calculation estimates and finite element modeling, are presented in WoodWorks' *CLT Diaphragm Design Guide*.



Collector strap from CLT diaphragm to core walls
at Platte Fifteen in Denver, CO



Installing spline tape at INTRO in Cleveland, OH

Further Information

This paper provides a brief summary of the new CLT diaphragm provisions in SDPWS 2021 and recommendations from the authors on their implementation. It is a companion to the more extensive *CLT Diaphragm Design Guide*, which includes the design of collector and chord details, full examples, and pre-calculated tables of connection capacities.

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