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PERFORMANCE-BASED SEISMIC DESIGN OF STEEL-TIMBER COMPOSITE STRUCTURES USING ENDURANCE TIME METHOD

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ABSTRACT: This paper investigates the seismic performance of Steel-Timber Composite (STC) frame structures using the Endurance Time (ET) method as a dynamic analysis technique. Motivated by the potential of replacing steel-concrete composite (SCC) systems with lightweight and sustainable alternatives, this study evaluates and compares the seismic response of STC and SCC systems. Three case-study buildings of different heights (3-storey, 7-storey, and 10-storey) are analysed through nonlinear pushover and ET time-history analysis. Timber-concrete hybrid floor slabs are replaced with engineered timber products such as Cross-Laminated Timber (CLT), connected via shear connectors to steel frames. The OpenSees platform is used for detailed modelling of nonlinear behaviour under earthquake excitations. The results indicate that STC systems significantly reduce seismic demand through decreased mass, leading to lower base shear and improved structural performance under dynamic loading. ET analysis effectively captures performance across a spectrum of intensities in a single run, proving to be an efficient tool for performance-based seismic assessment.

KEYWORDS: Steel-Timber Composite (STC), Endurance Time Method, Seismic Performance, Cross-Laminated Timber (CLT), OpenSees

1 – INTRODUCTION

The increasing uptake of hybrid timber structures in modern construction is largely driven by their structural efficiency, reduced environmental impact, and suitability for prefabrication. Engineered timber systems such as Cross-Laminated Timber (CLT) offer significant reductions in self-weight compared to traditional concrete systems, resulting in lower seismic inertial forces and more efficient structural design. Their lightness, combined with improved material availability and environmental performance, has made timber-steel composite (STC) systems a compelling alternative to conventional steel-concrete composite (SCC) solutions, particularly in seismic-prone regions [1,2].

One of the critical aspects of these composite systems lies in the performance of the shear connectors, which facilitate the composite action between the slab and the supporting beams. Past studies on cyclic loading of SCC systems have demonstrated that traditional headed stud connectors offer high stiffness and strength under reversed cyclic loading, which is critical for seismic applications [3,4]. However, the shear connectors used in STC systems—such as inclined screws, bolts, and notched connections—although showing promising ductile behaviour, often display lower initial stiffness due to the lower stiffness and density of timber compared to concrete [5–7]. Despite this, their ability to undergo large deformations without brittle failure provides a resilient structural mechanism during seismic events.

While several investigations have been conducted on the ultimate capacity [8–11], long-term deformation characteristics [12–15] and vibration performance [16–18] of STC beams, particularly under serviceability conditions, a significant gap remains in understanding their behaviour under earthquake-induced dynamic loading. This gap is especially critical given the increasing use of STC systems in mid-rise and high-rise applications where seismic forces are more pronounced.

Earthquake performance assessment methodologies vary in complexity and scope, ranging from simplified equivalent static force procedures to nonlinear time-history analyses [19]. Among these, nonlinear dynamic analysis provides the most realistic representation of structural behaviour under seismic excitations, though it is computationally demanding and requires detailed modelling and interpretation. Recent developments have introduced performance-based assessment tools such as the Endurance Time (ET) method [20–22], which enable

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the evaluation of structural systems under a single, intensifying ground motion record.

The ET method has gained attention for its efficiency in capturing both elastic and inelastic responses within a continuous and scalable simulation framework. It is particularly well-suited to assessing complex structures, including those with non-uniform stiffness distribution and nonlinear connections such as STC systems. The method eliminates the need for multiple ground motion records and allows designers to pinpoint the intensity at which performance thresholds are exceeded.

In this study, the ET method is applied to evaluate the seismic performance of STC frame structures and compare their behaviour with that of equivalent SCC systems. By combining nonlinear static (pushover) and dynamic (ET) analyses, this research aims to fill the existing gap in literature regarding the seismic resilience of hybrid timber systems and contribute to performance-based design strategies for sustainable and earthquake-resistant construction.

2 – Methodology

This section outlines the structural design, load combinations, modelling procedures, and seismic analysis methods employed to evaluate the performance of Steel-Timber Composite (STC) and Steel-Concrete Composite (SCC) structures. A combination of structural design standards, analytical software (Strand7 and OpenSees), and performance-based seismic assessment tools (pushover and Endurance Time Method) was used.

Table 1. Description of designed structural alternatives

No.	Frame Type/Direction			
Floors	SCC		STC	
3	SCC03X	SCC03Y	STC03X	STC03Y
7	SCC07X	SCC07Y	STC07X	STC07Y
10	SCC10X	SCC10Y	STC10X	STC10Y

2.1 Structural Design

The studied structure is a 40 × 40 m office building consisting of five 8-meter bays in both directions, with a storey height of 3.6 m. Three building heights were analysed: 3, 7, and 10 storeys. Each frame was designed in both STC and SCC configurations using CLT and RC floor systems, respectively. The buildings are assumed to be located in Seismic Region 1 (California, USA), requiring high seismic performance. The moment-resisting frame system was selected for its architectural flexibility and ability to provide open floor plans without braced walls.

Each floor system was assigned either a SCC or STC assembly, as shown in Table 1. All structures were designed for a 50-year design life, following ASCE 7-05 and AISC 360 guidelines. The moment frame was modelled with semi-rigid joints to reflect realistic rotational stiffness. The special moment frame (SMF) design was adopted due to the high seismicity of the region, requiring drift limitations and ductility provisions.

2.2 Load Combinations

Design loads were determined per ASCE 7-05. Dead loads included self-weight and superimposed loads (partition walls, finishes), with CLT assumed at 500 kg/m³ and concrete at 2500 kg/m³. Live loads for office use and flat roofs were 2.4 kN/m² and 0.96 kN/m², respectively. No live load reductions were applied for conservatism. Equivalent lateral forces were calculated using the base shear formula and vertical distribution per ASCE 7-05 §12.8. Seismic response coefficients were derived based on site classification, response modification factor (R), and building occupancy.

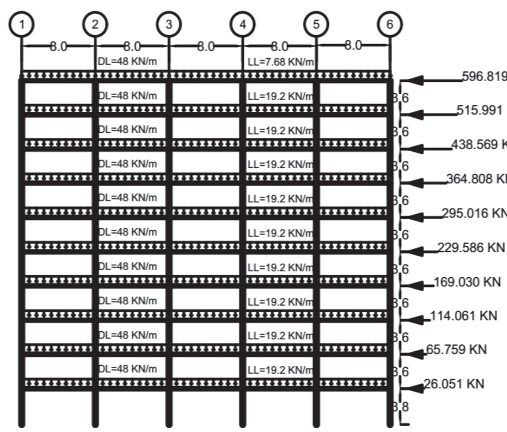

Figure 1. Ten-storey SCC frame in Y direction

The calculated dead, live, and lateral loads for STC and SCC structures at each height level are presented below. The seismic lateral forces were distributed in accordance with ASCE 7-05 equation (12.8-11), and the building periods were estimated using the empirical formula for moment frames. For dead loads, SCC frames carry 9.6 kN/m in the x-direction and 48 kN/m in the y-direction, whereas STC frames carry 6.08 kN/m and 30.4 kN/m in the x- and y-directions, respectively. Regarding live loads, the access floors are subjected to 3.84 kN/m in the x-direction and 19.2 kN/m in the y-direction, while the flat roof experiences 1.536 kN/m and 7.68 kN/m in the x- and y-directions, respectively. Figure

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1 and Figure 2 demonstrate loads applied to frames in x and y direction respectively.

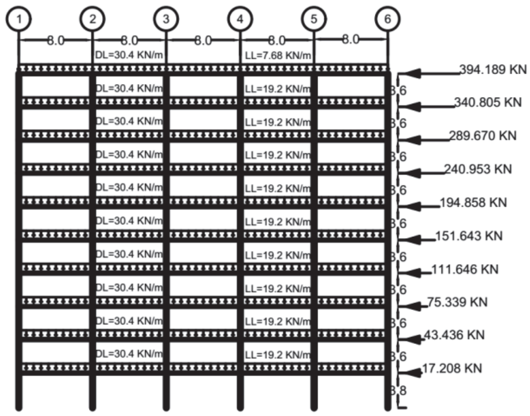

Figure 2. Ten-storey STC frame in Y direction

2.3 Structural Modelling & Analysis
2.3.1 Strand7 Modelling

Strand7 software was used to conduct linear static analysis and to size structural members. Structural steel sections were modelled using ASTM A572 Grade 60 with a minimum yield strength of 415 MPa. Beams and columns were defined as AISC W-sections. Shear connectors (bolts or screws) were modelled using spring-damper systems to connect steel beams to CLT or RC slabs. Composite forces and design limits were checked based on AISC 341-05 and AISC 360-05. Different sections were selected for each storey level to simplify design: the bottom (1–4), middle (5–7), and top (8–10) levels had unified member sections. Table 2 and Table 3 present the final section design for SCC and STC 10-storey frames. Interstorey drift ratios were monitored to ensure compliance with the allowable 0.02 drift ratio per ASCE 7-05 Table 12.12-1 (see Figure 3 to Figure 5).

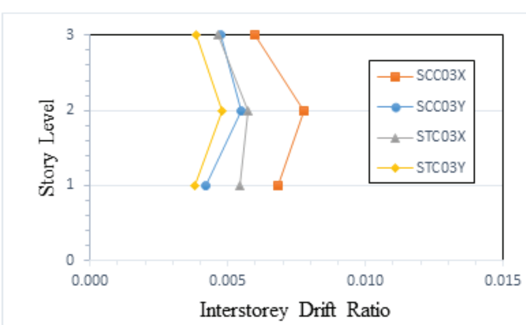

Figure 3. Maximum interstory drift ratio of 3-storey frames at different storey levels obtained by Strand 7 analysis.

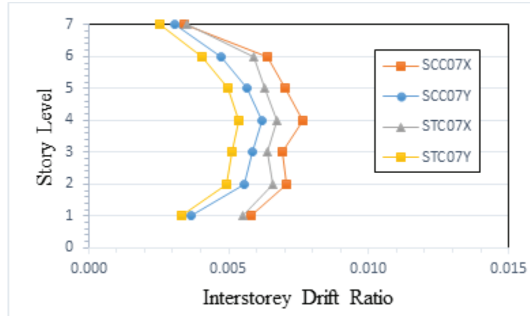

Figure 4. Maximum interstory drift ratio of 7-storey frames at different storey levels obtained by Strand 7 analysis.

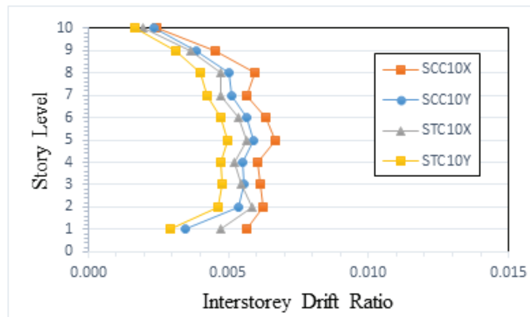

Figure 5. Maximum interstory drift ratio of 10-storey frames at different storey levels obtained by Strand 7 analysis.

2.3.2 OpenSees Modelling

OpenSees was employed for nonlinear modelling and time-history-based performance assessment. Nodal geometry was defined programmatically using MATLAB scripts to streamline generation of floor levels and beam-column connections. Beams and columns were modelled using nonlinear beam-column elements with fibre section definitions, capturing yielding and local buckling. Material models for steel incorporated bilinear kinematic hardening to represent cyclic degradation.

CLT slabs were defined as orthotropic plates, using CONCRETE02 material model with appropriate shear stiffness and tension-softening properties. Shear connectors were modelled using zeroLength elements with spring properties calibrated to experimental stiffness and strength of bolts or screws. To ensure realistic floor behaviour, rigid diaphragm constraints were applied at every floor level. The seismic mass was lumped at floor nodes, consistent with the rigid diaphragm assumption. The natural period of each model was computed to scale input ground motions and verify compliance with design codes.

Table 2 The section design for 10-storey SCC frames

SCC10	Interior columns	Exterior columns	Interior beams (X)	Exterior Beams (X)	Interior beams (Y)	Exterior beams (Y)
1-4 storey	W14×500	W14×370	W24×162	W24×103	W24×146	W24×94
5-7 storey	W14×370	W14×145	W24×131	W24×94	W24×117	W24×84
8-10 storey	W14×233	W14×145	W24×94	W24×84	W24×84	W24×76

Table 3 The section design for 10-storey STC frames

STC10	Interior columns	Exterior columns	Interior beams (X)	Exterior Beams (X)	Interior beams (Y)	Exterior beams (Y)
1-4 storey	W14×398	W14×311	W21×147	W21×111	W21×132	W21×101
5-7 storey	W14×311	W14×132	W21×122	W21×93	W21×111	W21×83
8-10 storey	W14×211	W14×132	W21×93	W21×73	W21×83	W21×68

2.4 Pushover Analysis

Pushover analysis was performed to estimate structural capacity and identify failure mechanisms. A lateral load pattern proportional to mass height distribution (mode shape approximation) was applied incrementally until global instability or strength degradation was observed. Uniform lateral load pattern was also assessed for sensitivity.

Base shear vs. roof displacement curves were extracted to determine global stiffness, ductility, and overstrength. Plastic hinge formation and drift profiles were recorded at each load step to identify critical failure zones. The analysis provided insight into system-level ductility and energy dissipation capacity of STC and SCC systems.

2.5 Endurance Time Method

The Endurance Time (ET) method was utilised for seismic assessment by subjecting the structure to a single intensifying artificial acceleration function. The ETA20f01 record, tailored to match the average response spectrum for FEMA 440 soil class C, was used for all cases. This method allows evaluation of structural behaviour across a spectrum of seismic intensities within one analysis.

The ET method involved scaling input acceleration based on the fundamental period of each model. Structural response metrics such as interstorey drift, roof displacement, and internal forces were extracted at defined time intervals. This allowed mapping performance thresholds to equivalent seismic intensities. The ET approach is particularly useful for performance-based design as it captures both elastic and inelastic responses efficiently. It eliminates the need for multiple ground motion records and intensity levels, offering a computationally efficient and consistent methodology for comparing STC and SCC performance under seismic loading. Figure 6 and Figure 7 represnet acceleration function and acceleration response spectra for ETA20f01 time series.

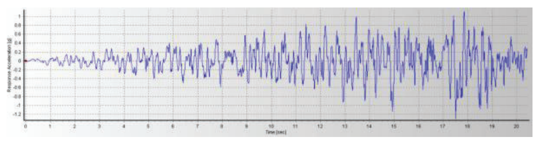

Figure 6. ETA20f01 accleration function

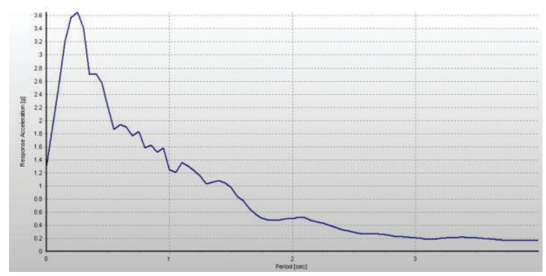

Figure 7. ETA20f01 acceleration response spectra

3 – RESULTS

3.1 Pushover Analysis

Figure 8 through Figure 10 illustrate the pushover curves for 3-, 7-, and 10-storey STC and SCC frames under nonlinear static loading. These force-displacement curves provide insight into the elastic and inelastic performance of both structural systems.

The pushover analysis revealed notable differences in the structural response of STC and SCC frames, particularly in relation to building height. For lower-rise buildings, STC frames exhibited lower yield points and more ductile behaviour, characterized by early yielding and a longer displacement plateau, whereas SCC frames demonstrated a stiffer response with increasing base shear as lateral displacement increased. This distinction was most pronounced in the 3-storey models, where the

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reduced mass of the STC system significantly influenced the seismic performance. However, as the number of storeys increased, the pushover curves for both systems began to converge, indicating that building height becomes the dominant factor influencing structural behaviour. This trend can be attributed to the increase in natural period with building height, which reduces the overall seismic demand, thereby diminishing the relative impact of mass differences between the systems. For instance, in the 7-storey case, the STC frame carried approximately 15% less lateral force than the SCC frame for corresponding displacement levels, demonstrating the continued, albeit reduced, benefit of lighter construction. These findings underscore the importance of considering both structural system and building height in seismic design, as mass-related advantages of STC frames are more influential in shorter buildings, while dynamic characteristics take precedence in taller structures.

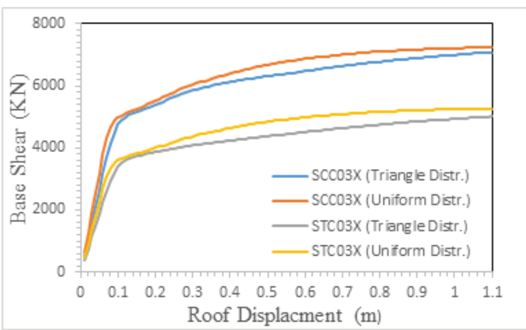

Figure 8. Pushover curves of the 3-storey frames

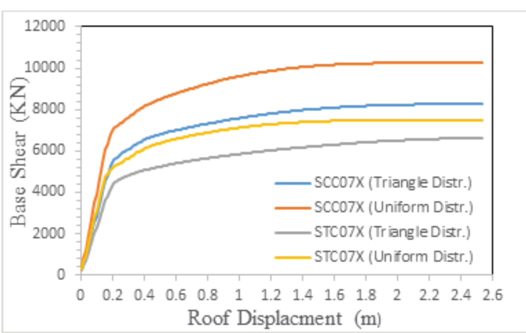

Figure 9. Pushover curves of the 7-storey frames

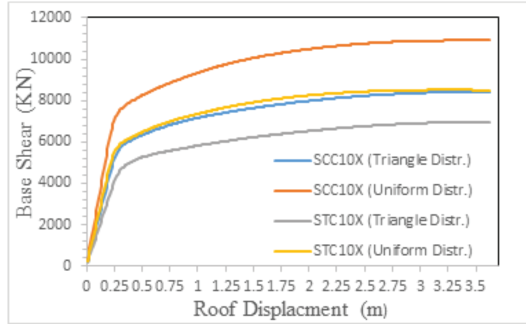

Figure 10. Pushover curves of the 10-storey frames

In terms of effective lateral stiffness, STC systems exhibited a reduction of approximately 10–20% compared to SCC, which is attributed to the lower stiffness of CLT panels in comparison to reinforced concrete slabs. Nevertheless, the trade-off was balanced by the improved displacement capacity and energy absorption capabilities observed in the STC frames. These characteristics are vital for structures designed in regions with high seismic demand.

Storey drift profiles extracted from the analysis indicate that both STC and SCC systems remained within the allowable drift limits of 2% as per ASCE 7-05, with STC frames consistently achieving slightly lower peak drift ratios across all heights. For the 10-storey model, the maximum interstorey drift in the STC frame was observed at 1.7%, compared to 1.95% for the SCC counterpart, suggesting enhanced seismic resilience in taller STC systems.

However, the results also highlighted key limitations in the pushover analysis method. As expected, the accuracy of the analysis decreased with building height due to the increasing influence of higher-mode effects, which are not well captured in conventional pushover procedures. This was particularly evident in the lateral force distribution, where the assumed load patterns failed to accurately replicate the multi-modal behaviour observed in real seismic events. Thus, dynamic methods such as the Endurance Time (ET) method are necessary to validate and supplement the static pushover findings.

3.2 Endurance Time Analysis

Figure 11 through Figure 13 present the ET analysis results for roof displacement under increasing seismic intensities. The ET curves capture the progression of structural deformation as the intensity of applied ground

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motion increases, providing a comprehensive view of both elastic and inelastic responses.

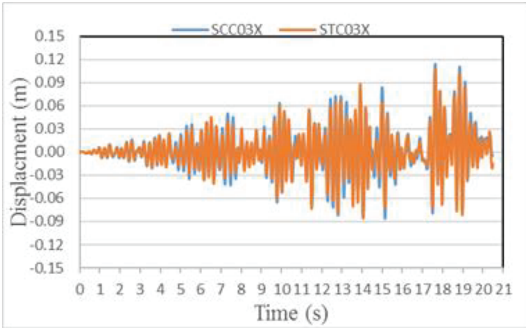

Figure 11. ET curves from roof displacement of 3-storey frames

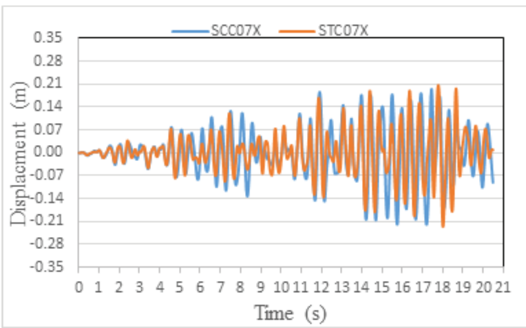

Figure 12. ET curves from roof displacement of 7-storey frames

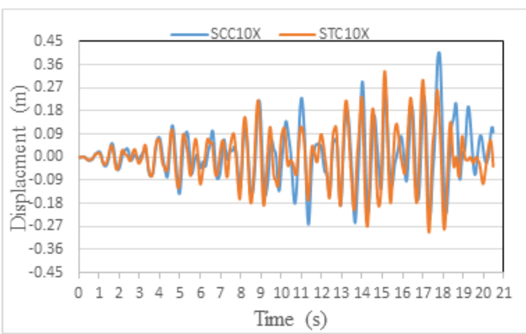

Figure 13. ET curves from roof displacement of 10-storey frames

In all building heights, STC frames consistently demonstrated lower roof displacements at corresponding intensity levels. For the 3-storey frames, the peak displacement of the STC frame remained approximately 12% lower than that of the SCC frame. At the 7-storey level, the displacement advantage grew to nearly 18%, indicating the increasing performance divergence as building height and structural demand rise.

For the 10-storey structures, the STC frame displayed up to 22% lower peak displacement compared to its SCC counterpart. Moreover, the STC response curve revealed a smoother transition into nonlinear behaviour, suggesting a more ductile and stable response. The onset of rapid displacement accumulation—indicative of structural yielding—was delayed in STC systems, reflecting their improved capacity to absorb and dissipate energy under severe seismic loads.

The ET results also revealed significant differences in residual drift at the end of the acceleration history. Residual drift in SCC frames was consistently higher, suggesting that STC frames are more likely to return to their original configuration post-earthquake, which could reduce repair demands and downtime.

Time-history snapshots of interstorey drift ratios showed that STC systems maintained more uniform drift profiles along the building height. SCC systems, on the other hand, exhibited concentration of drift in mid-storeys, increasing the risk of localised failure. This is likely a result of higher mass and stiffness contrast in SCC configurations, which may trigger soft-storey mechanisms under certain loading scenarios.

While the current ET analysis employed a single intensifying ground motion (ETA20f01), its results were found to be consistent with known behavioural trends of light-frame composite systems. Nonetheless, for robust performance evaluation, future work should incorporate a suitable ET-compatible records optimized for regional seismicity and soil conditions. This would allow sensitivity analysis and enhance the generalizability of findings.

Overall, the ET method proved highly effective for comparing STC and SCC systems under realistic seismic loading conditions. The clear advantages in displacement control, ductility, and residual drift observed in STC systems further validate the potential of timber-steel hybrid construction in seismic regions.

4 – CONCLUSION

This study assessed the seismic performance of Steel-Timber Composite (STC) and Steel-Concrete Composite (SCC) frame structures for 3-, 7-, and 10-storey buildings using the Endurance Time (ET) method and pushover analysis. Finite element modelling incorporating deformable shear connectors was found essential for accurately simulating the nonlinear behaviour of composite systems, as these connectors significantly affect load transfer and ductility, particularly in STC systems. The reduced self-weight of STC frames results in lower base shear forces and smaller displacement demands, thereby enhancing seismic resilience and reducing steel usage, which makes STC systems

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structurally and economically beneficial. The ET method proved to be a powerful tool for performance-based seismic assessment by enabling efficient simulation of progressive damage and nonlinear deformation, capturing both elastic and inelastic behaviour in a continuous manner; spectral matching and time-scaling techniques adopted in the study were effective for regional seismic design. The analysis assumed a rigid diaphragm that evenly distributes lateral forces between structural frames; however, due to the lower stiffness of cross-laminated timber (CLT) compared to concrete, STC floor systems may require special detailing to satisfy diaphragm rigidity requirements.

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