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Direct displacement design of tall cross laminated timber platform buildings with inter-story isolation

Vahab Bolvardi [a,*], Shiling Pei [a], John W. van de Lindt [b], James D. Dolan [c]

[a] Department of Civil and Environmental Engineering, Colorado School of Mines, Golden, CO, USA
[b] Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO, USA
[c] Department of Civil and Environmental Engineering, Washington State University, Pullman, WA, USA

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ABSTRACT

Cross Laminated Timber (CLT) is a relatively new engineered wood material viable for the tall building construction. Currently, existing multi-story CLT buildings are mostly built in regions with low seismicity. Due to the lightweight nature of the wood material, CLT buildings have a relatively lower seismic force demand and great potential to achieve resilient performance in earthquakes. This study explores the potential use of an inter-story isolation system to achieve seismically resilient performance in platform tall CLT buildings. A generalized Displacement-based Direct Design (DDD) procedure was modified to identify key design parameters of the inter-story isolation system so that the building can achieve preselected displacement targets. The proposed design procedure was applied to a 12-story CLT building design example using Los Angeles, CA seismic hazard parameters. The as-designed building performance was validated numerically through nonlinear time history simulations.

1. Introduction

The majority of low-rise residential buildings in the U.S. were built with wood material. Current building codes in most jurisdictions only allow light-framed wood buildings up to four or five stories, with more restrictions in high seismic regions [1]. Tall buildings in the range of 10–20 stories have been building exclusively with steel and concrete materials in the past. A relatively new engineered mass timber product, namely Cross Laminated Timber (CLT), provided an opportunity to construct tall buildings with wood [2]. CLT is a glue-laminated panelized wood product with lamination thickness ranging from 1.9 to 6.35 cm. Panelized CLT system provides dimensional stability, sufficient strength and rigidity. CLT can be used as floor diaphragms, roof panels, and load-bearing walls in a building. It can also be combined with other mass timber produces such as glulam beams and columns. A number of existing tall CLT buildings (e.g., Forte building in Melbourne Australia, Stadthaus Building in London) used exclusively CLT panels as both the wall and floor components. The CLT walls are separated by the CLT floor diaphragms at each story, making this a platform style CLT construction.

Most of the existing tall CLT platform buildings are located in regions of low seismicity. Currently, the understanding of a CLT building system behavior under seismic loading is limited compared to other existing structural systems, even with a significant amount of research conducted in recent years (e.g., Ceccotti et al. [3], Dujic et al. [4,5], Fragiacomo et al. [6], Hristovski et al. [7], Rinaldin et al. [8], Sustersic et al. [9], Vessby et al. [10], Reynolds et al. [11]). A comprehensive review of existing seismic research on the CLT building system up to 2014 can be found in Pei et al. [12]. These past studies highlighted the challenge in obtaining ductility in CLT lateral resisting system without incurring connection damage. This is mainly due to the fact that the CLT panel itself is relatively rigid and the main source of ductility in current CLT buildings is the plastic deformation of the connections. This characteristic makes it difficult to achieve a high level of performance, such as resilience, in large earthquakes (i.e., connections will get damaged). In this study, an alternative way to incorporate ductility for tall platform CLT buildings in form of inter-story isolation system was proposed. A Direct Displacement Design (DDD) procedure for CLT buildings with inter-story isolated system was developed (based on an existing DDD approach for non-isolated multi-story buildings). The design process seeks to achieve different displacement limitation targets for the regular CLT stories and the isolation layer simultaneously. As an illustrative example, DDD of a twelve story CLT building located in Los Angeles, CA was conducted and

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[*] Corresponding author.

E-mail addresses: vbolvard@mines.edu (V. Bolvardi), spei@mines.edu (S. Pei), jwv@engr.colostate.edu (J.W. van de Lindt), jddolan@wsu.edu (J.D. Dolan).

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numerically validated through nonlinear time history analysis (NLTHA).

Seismic isolation is an effective method to mitigate building damage during earthquakes. While isolation systems are mostly implemented at the base, there are benefits to apply inter-story isolation systems as well. An inter-story isolation system eliminates the need for expensive foundation work, enables reduction of story shear demands and provides protection to the isolated segments. Ryan et al. [13] conducted numerical analyses on nonlinear inter-story isolation systems and evaluated the viability of using existing base isolation devices available in the market. It was concluded in Ryan et al. [13] (through analysis of a series of simple shear-building models with isolation) that placing isolation system in the lower half of the structure (particularly at the base or first story) is more efficient than at other locations in term of limiting seismically induced force within the system. Inter-story isolation has been adopted in several real building applications around the world, such as 185 Berry Street in San Francisco [14] (two additional stories isolated on top of an existing three-story building), and the Idabashi First Building in Tokyo, Japan (5 additional stories isolated on top of a 9-story multifunction building) [15]. Design of inter-story isolation systems falls into the category of specialty performance-based design. There has not been a generalized Performance-Based Seismic Design (PBSD) approach that can be applied to the inter-story isolation system design for tall buildings.

Direct Displacement-based Design (DDD) method is a potential candidate for inter-story isolation design due to its ability to explicitly control displacements. It has been introduced firstly by Priestley [16] as an alternative design method to NLTHA based approaches for concrete structures. This method was then ported to light-framed wood structure design by Filiatrault and Folz [17]. It was later used by Pang et al. [18] for PBSD of mid-rise light-framed wood structures. Pang et al. [19] further simplified the DDD procedure to design the shear walls for a six-story wood frame structure by neglecting higher mode effects and verified the design requirements through NLTHA. A full-scaled physical specimen of the six-story wood building was also tested experimentally using shaking table [20]. Specifically, for platform CLT buildings, the DDD approach was used by Pei et al. [21] to achieve specific inter-story drift performance targets. In that study, the nonlinear load-displacement backbone curves for typical CLT panel walls were developed using a mechanistic model calibrated by CLT wall test data. DDD methodology has also been applied to base isolation system design. Cardone et al. [22,23] applied this methodology to design of buildings and bridges with base isolation.

Existing panelized CLT construction usually uses metal hardware brackets to connect wall and floor panels. Tests of CLT panel walls conducted by Popovski et al. [24] revealed that shear deformation of CLT panel itself was negligible compared to the deformation at panel connections. Thus, lateral displacement of a CLT panel was mainly the result of the panel rigid body rotation about the corners. As a result, the strength and ductility of CLT shear walls are mainly controlled by the connection strength and the aspect ratio of the panels. Pei et al. [25] developed a simplified model for isolated CLT shear walls and calibrated the model with tests data from Popovski et al. [24]. Based on this model, Pei et al. [26] conducted further investigation and proposed a way to gain ductility in panelized CLT construction, which requires long CLT shear walls with low height-to-length aspect ratio be divided into shorter segments so that individual segments can rotate by themselves. However, this will require installation of individual short panels to form a long wall, involving more connections at the panel interface as well as more effort to align multiple panels together. This pathway to ductile performance will likely increase construction time and cost. On the other hand, the inherent rigidity in CLT walls and floor diaphragms (relative to light-framed wood systems) can be an opportunity for incorporating inter-story isolation, which will shift earthquake displacement demand to the isolation layer and protect low-ductility CLT stories with rigid single-panel long walls from damage. Although isolation system will be an added cost, it is possible to leverage on the modular nature of CLT construction by developing a modular "sliding floor" system that can be prefabricated as a standard isolation unit for multi-story CLT buildings.

The key for isolated CLT building design is to control the deformation of the isolation layer and the CLT stories. The design constraints for isolated CLT buildings are explicitly displacement-based. In this study, a generalized DDD procedure developed in earlier studies on wood frame building was updated to enable inter-story isolated CLT platform building design. The procedure was applied to the design of a 12-story CLT building in Los Angeles, CA. The as-designed building performance was validated numerically through nonlinear time history simulation.

2. Direct displacement design methodology for inter-story isolation system

When applying inter-story isolation, the expected building performance will likely be higher than merely ensuring life-safety. It is assumed in this study that the proposed DDD procedure will be used to achieve resilience (i.e., minimum damage). Under this assumption, most of the nonlinear displacement and energy dissipation will occur at the isolation layers, while the rest of the CLT building will remain close to elastic behavior. When only one isolation layer is present, a multi-story system can be simplified into an equivalent 3-DOF system as shown in Fig. 1.

In case of platform CLT building design, the building seismic mass can be roughly determined once the architectural design is complete. The stiffness of the CLT stories can be calculated based on the amount of CLT panelized walls specified in the architectural floor plan (following the procedure in Pei et al. [21]). With the mass and stiffness distribution known, the properties of the top and bottom equivalent single degree of freedom (ESDOF) system can be determined through linear modal analysis (using the first mode) of these segments respectively. After the equivalent 3DOF (E3DOF) was obtained, the simplified DDD procedure proposed in Pang et al. [19] can be used to identify the design parameters for the isolation layer needed to achieve target displacement. The general steps for conducting DDD of inter-story isolated CLT building are summarized below. Note that Steps 3 and 4 are developed specifically for inter-story isolated CLT buildings and unique to this study, while the other steps are existing procedures in simplified DDD included here for clarity:

2.1. Step 1: Select displacement targets

Desired displacement limits for the regular CLT stories and the isolation system should be selected for different seismic hazard levels. A Non-Exceedance (NE) probability should be assigned to each displacement level. An example of such displacement targets is shown in Table 1. Note that the seismic hazard levels corresponding to different hazard exceedance probabilities were used in this example. Although three levels of seismic hazard were considered here, the design procedures for each of these hazard levels are the same. One of the target performance levels will eventually control the design.

2.2. Step 2: Calculate the adjustment factor for specified Non-Exceedance (NE) probability of design spectral acceleration

The ASCE/SEI-7 (American Society of Civil Engineers, 2010) design response spectra represents the median demand (50

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