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Assessment and comparison of experimental and numerical model studies of cross-laminated timber mechanical connections under cyclic loading

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HIGHLIGHTS

- Cross-laminated timber connections were tested and modeled with finite element model.
- Test and model results were analyzed with two assessment methods to evaluate the model.
- The equivalent energy elastic–plastic model showed good correlation of test and model.
- The cumulative energy method is more precise to evaluate hysteretic models.

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ABSTRACT

Earthquake engineering is a major consideration for structures along the west coast of North America. The current building code of Canada is based on design criteria, which are defined by stresses and member forces calculated from prescribed levels of applied lateral shear force. Traditional wood-frame buildings are known to perform well in earthquakes. However, with the development of new engineered wood products, such as CLT (cross-laminated timber) and more consideration to build higher than the existing six stories limit in wood-frame structures, highlights the need to use innovative hybrid techniques for buildings. Hybrid buildings with steel frame structures incorporated with CLT infill walls offer one possible solution to residential and commercial multi-level buildings to overcome the height limitation. In order to make such a structure applicable for an earthquake prone area, it is important to understand the structural performance of the connection between steel and CLT elements. In this research, six connection combinations have been tested and modeled in a finite element program. The load–displacement test results are assessed with two evaluation methods. The first method follows the American Society of Testing Method, where ductility ratio, elastic shear stiffness, and the *EEEP*-curve (equivalent energy elastic–plastic curve) are generated and assessed. The second method follows an energy-based accumulation principle, where the test results are used to calculate a damage index at each time step. Both methods are used to compare test and model results and assess the accuracy of the model as well as addressing the capability of each assessment method. Depending on the purpose of the model one or the other assessment method might be suitable. For an analysis of the overall ductility or elastic shear stiffness, applying the method provided by ASTM will give relatively accurate results to assess a hysteretic load–displacement model such as the SAWS model in this research. The assessment with a damage accumulation method is a great tool to capture more details of the hysteretic load–displacement curve. Energy dissipation is valuable indicator besides ductility and elastic shear stiffness to evaluate the model.

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1. Introduction

Earthquakes resistant engineering is a major consideration for structures along the west coast of North America. Especially higher buildings need to be properly designed, in order to provide serviceability or life safety in a seismic event. Generally, wood-frame

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buildings are known to perform well in earthquakes [24]; however, there are limitations under code that prevent the use of wood framing in all desired building designs. For instance, the provincial building code of British Columbia (BC) limits multi-story wood frame buildings to a maximum height of six stories [3]. The current code is based on design criteria, which are defined by stresses and member forces calculated from prescribed levels of applied lateral shear force [15]. Innovative hybrid techniques, where steel frame structures are incorporated with cross-laminated timber (CLT) infill walls, offer one possible solution to residential and commercial multi-level buildings to overcome the six-storey height limitation [7,28].

Seismic demand and seismic capacity of a structure are important factors for the design procedure. Timber-frame structures are relatively lightweight structures that obtain their great seismic performance through ductile connections between studs and sheathing, which provide sufficient ductility to the shearwall system through a variety of load paths [24]. CLT shearwall panels, however, are relatively rigid bodies with no studs or sheathing; therefore, different methods and connections must provide ductility and energy dissipation. CLT wall-to-floor connections are designed using L-shaped steel brackets, which are nailed or screwed to the CLT wall panel on one side, and bolted to the floor on the other side of the bracket. To apply such bracket connections within a CLT-based hybrid structure (Fig. 1), comprehensive understanding of their structural performance under reversed cyclic loading is required (e.g. [9,26]).

Performance-based design is a methodology, where structural design criteria have to achieve a certain level of performance [15]. Damage, displacement, or drift, which are easily measurable, can be related to such performance objectives. However, to measure and evaluate damage is more complex undertaking. Damage is influenced by accumulation of structural damage, variation of failure modes of the structural components, and number of cycles before failure occurs [30]. One possible way to assess and evaluate is the introduction of damage indices (e.g. [25]). Beyond calculating the maximum capacity prior to failure of a connection, it is also important to characterize and understand the path to failure (e.g. what is damage? How can damage be quantified? Are there intermediate damage stages before collapse? How does a load–displacement curve of a cyclic loading protocol relate to damage progression over time?).

Over the years many different damage assessment attempts have been made (Table 1). Damage indices are categorized into global and local damage indices. Global damage indices describe the overall damage state of a structure, whereas local damage indices describe the damage which occurs in an individual member or joint between adjacent members.

Damage can be measured in relation to curvature, rotation, energy or displacement. For most damage principles, a damage index D is calculated. The goal of damage indices is to provide a means of quantifying numerically the damage under earthquake loadings [30]. The damage index has to be calibrated and should range between zero and one. Zero represents no damage, where one is considered collapsed or destroyed.

In previous research, the damage index was computed at one point after the entire loading procedure was completed (e.g. [19]) Schneider et al. [25] investigated six connection types and developed a damage scale for Kraetzig's energy-based damage index (Table 1). The proposed preliminary damage scale distinguished five damage limit states: None, Minor, Moderate, Severe and Collapse (Table 2). The proposed prediction scale applying Kraetzig's damage accumulation model is necessarily limited to the connections tested; however, it provides a preliminary approach for pre-

Table 1
Categories of damage principles.

Damage principle	Description	References
Non-cumulative indices	The model neglects the effect of repeating cycles that occur in earthquakes	[30]
Deformation-based cumulative indices	Models connect damage directly to the displacement or rotation of an element or structure	[29,30]
Energy-based cumulative indices	Models consider the energy absorption in a system or element under cyclic loadings	[16,18,30]
Combined cumulative indices	Combined models consider displacement and energy absorption in one index	[22,30,21]

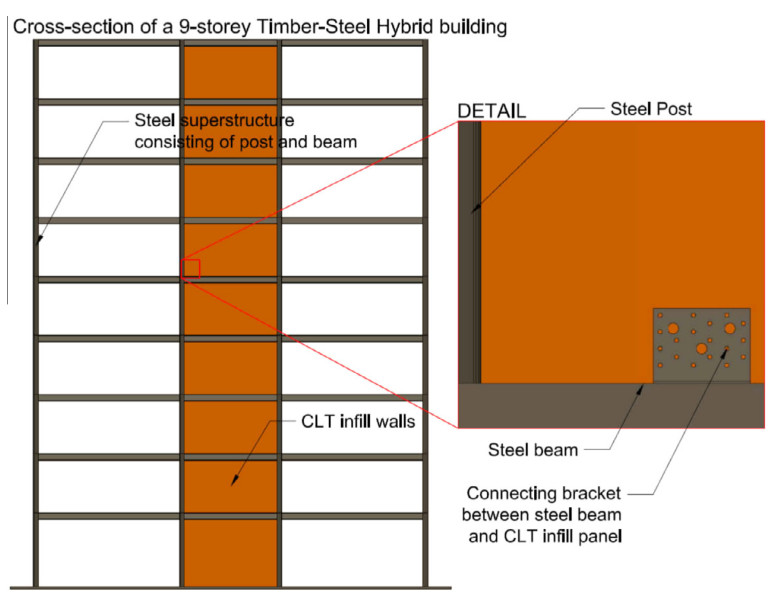

Fig. 1. Proposed timber-steel hybrid structure.

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