Studying the Seismic Behavior of Cross Laminated Timber

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Abstract

Cross laminated timber (CLT) is made up of layers of timber glued in an alternating configuration, which makes it advantageous for loading in both directions. Despite the desirable properties of CLT, its use in tall structures located in highly seismic active regions is uncommon. To confirm the possibility of using CLT in tall structures, a rocking wall incorporated two-story tall structure is tested at University of California, San Diego's Large High Performance Outdoors Shake Table. After simulating the 1994 Northridge earthquake at 125%, the structure still stands with damages, such as cracks and crushing, in the beams and columns. Upon the positive results, further testing will be conducted in order to develop a test-validated methodology for constructing tall CLT structures in seismically active regions.

Introduction

Cross laminated timber (CLT) is a fairly new structural material that's dominantly used in Europe, however there is a surge of interest in this material in North America (Strauder 1). CLT is a structural member with layers of timber glued together at a crosswise (90 degrees) configuration (figure 1). Such a configuration allows CLT to be strong and rigid, which makes it desirable for lateral and vertical load resisting systems. In comparison to other structural materials such as steel and concrete, CLT is just as structurally strong but is also cost and environmentally friendly. The ease and speed of construction makes this material desirable choice (Popovski and Karacabeyli 1). These benefits and advantages of CLT drives the research and desire for exploring its structural usage. Currently, tall CLT structures are being built all around the world. The University of British Columbia is currently constructing an 18-story structure that will serve as housing for its students (Gintoff). In Brisbane, Australia, a 10-story office building is being built out of CLT (Opray). A 12-story CLT structure will be built in Portland, Oregon which will be the first CLT structure of this height to be built in the United States (Rosenstock). These are only a few examples of the interest and step towards this new structural material. However, the use of CLT in tall structures located in high seismic regions is still uncommon (Pei, 6).

Figure 1. Method how CLT is assembled

Source: Mallo, Maria F. L. Alternating Perpendicular Directions of Layers in Cross Laminated Timber. Digital image. *MS Thesis*. University of Minnesota, 2014. Web. 27 July 2017.

The rocking wall incorporated two-story CLT structure that was tested at the University of California, San Diego Englekirk Structural Engineering Center's outdoors shake table is the starting point for developing test validated design methodology for CLT structures and opening doors to further research and the expansion of the structural usage of CLT in North America. This study will focus on the seismic resilience of CLT during the 1994 Northridge earthquake in comparison to other structural materials such as steel and concrete.

Description of the Test

A two-story tall structure is built with CLT was the main structural material and the connections are made of steel. The roof of the structure has a 2.25in thick layer of concrete with a strength of 5 ksi. The floors are about 20ft by 58ft. The first story is about 13ft tall, while the second story is about 10ft tall. The roof panels are made up of 5 ply timber and the first story panels are made up of 3 ply timber. Four continuous columns (at the center of the structure) and four discontinuous columns (towards the edge of the structure) are used to support the structure, creating both balloon and platform framing in the structure. The structure has two cantilevered sections and are minimally braced with rods crossing the center (figure 2). The connections are either bolted or welded together. Another key feature of the structure is that there's two rocking walls situated at about 19 feet from the edges. These rocking walls are made up of two panels that rock independently from one another. They are connected to the diaphragm by placing a steel tongue through the wall, acting as a lateral force resisting system. This allows the rocking of the walls to influence the diaphragm too. The structure was built on top of a three feet tall beam which is fixed to the shake table. The purpose of this is simply to expand the shake table so that it can hold a structure of this size.

Figure 2. Test structure after the completion of construction and installation of sensors

The structure is loaded with about 90 kips of dead loads through steel plates. The structure was tested different ground motions of increasing intensity, such as the 1994 Northridge earthquake and the 1989 Loma Prieta earthquake. The table is only limited to movement in one direction (east-west direction).

The analysis of the structure will be conducted by measuring the displacement of the structure. These measurements will be conducted by using various sensors such as linear potentiometers, spring potentiometers, and string potentiometers. These sensors are generally placed at the points of interest, such as the splices of the slabs, the corners of the structure, the columns, and throughout the rocking walls. Specific sensors were chosen due to the degrees of freedom that are provided with the instrumentation. The acceleration of the structure is measured using accelerometers. There’s over 350 sensors attached to the structure.

Results

The 1994 Northridge test at 125% strength was conducted on the CLT structure at the shake table. Only minor damage and no major structural damage was found on the structure. Small cracks and splitting of the timber’s grains were found near the connections of the beam and columns (figures 3, 4, and 5)

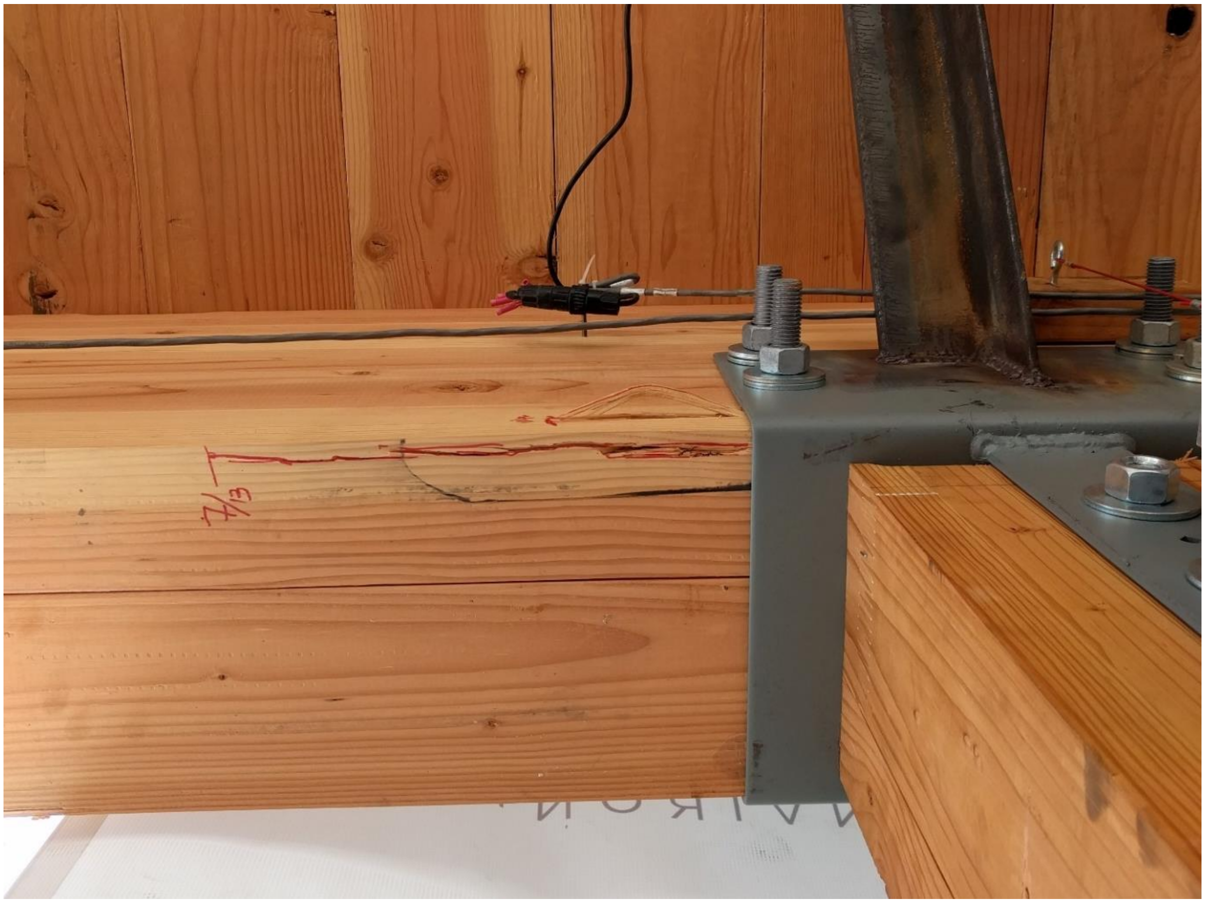

Figure 3. Crack and small splitting at a beam located on the NE section of the second floor (looking from ground up)

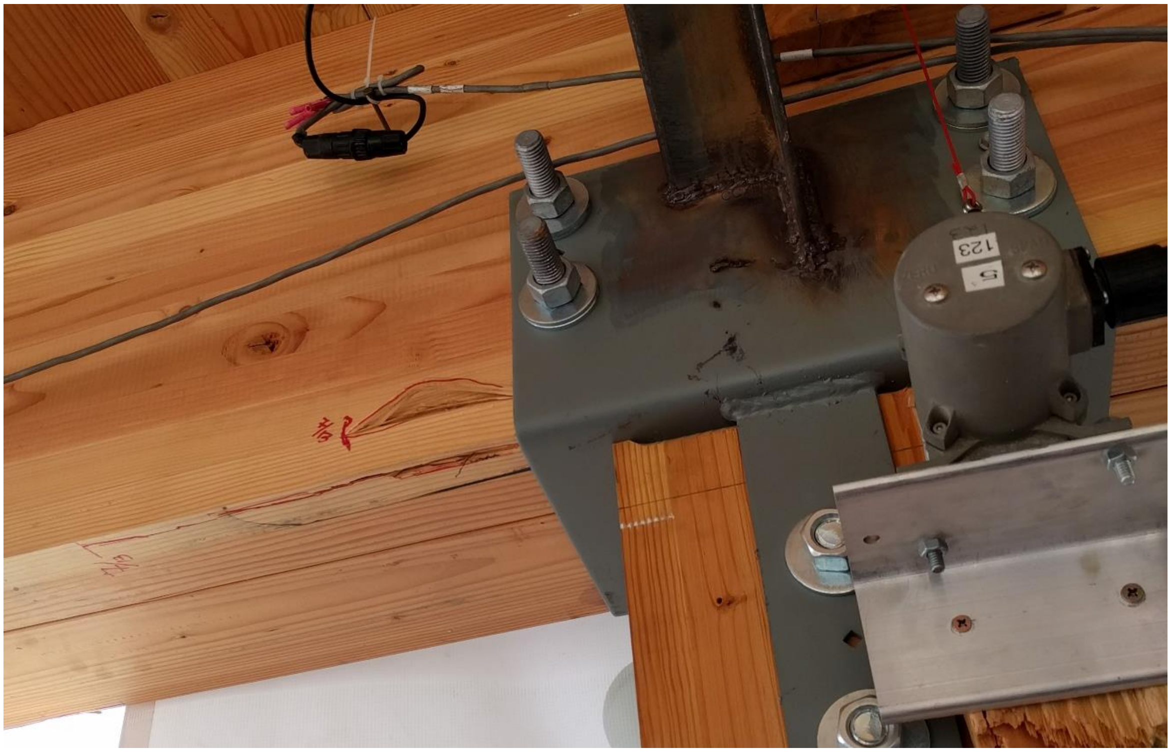

Figure 4. Small splinter of the beam near the connection (Same damage documented in figure 2)

Some crushing was found at the bottom corners of the rocking walls (less than an inch). Other damages due to crushing on the walls ranged from 3 to 5 inches (figure 6). Minor rounding of the corners was seen at the foot of the columns and the rocking walls (less than half of an inch). Small separation of about 1 to 3 millimeters between the CLT pieces was found on the walls and columns (Figure 5). Majority of the damage on the CLT was found on the second floor rather than the ground floor.

Figure 5. Wood splinter at the bottom of the discontinuous column and separation of the lamination located at the NW section of the second floor

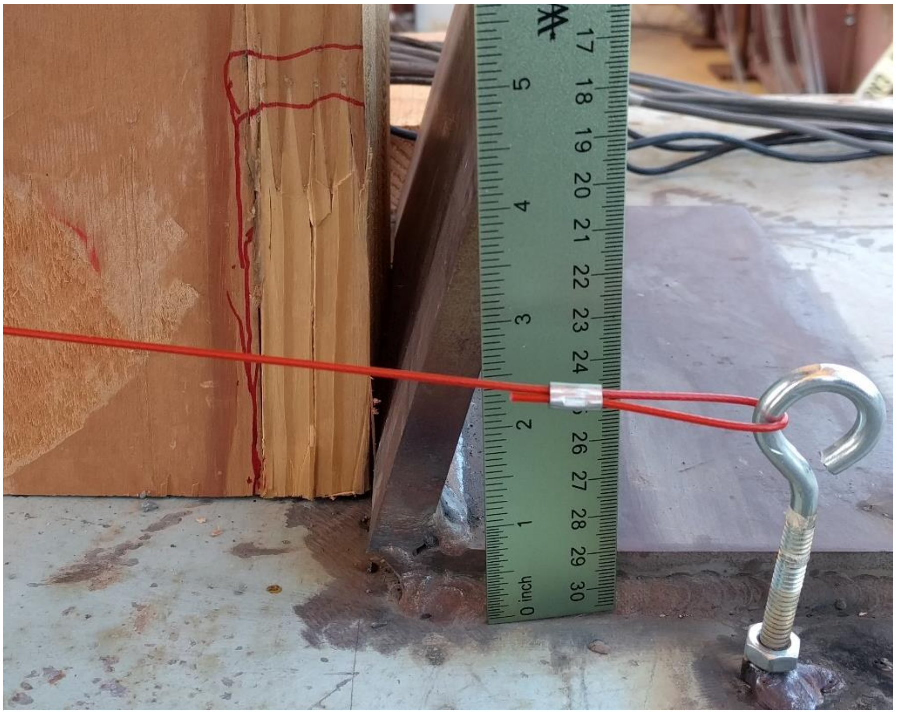

Figure 6. Toe crushing found at the foot of the rocking wall (north face of the NW panel)

Discussion

From this test, it can be noted that damage typically occurred near the connections and joints of the structural members. As the walls rock about their corners, the structure experiences uplift and shear. Such effects caused damages in the columns, beams, and the walls of the structure. The crack shown in figure 2 is due to flexure in the beam since the damage is perpendicular to the grain. The wood splitting in the columns in figures 2 and 4 may be a result of crushing in the members. Such results reflect the conclusions that Pei found in researching CLT in that uplift during earthquakes can cause severe damage to connections (6). Despite such damages, these are merely surface damage and do not threaten the structural integrity of the CLT building at all.

To conduct a comparison, damage due to the 1994 Northridge earthquake in steel and concrete structures will be observed. After the Northridge earthquake, steel moment frames didn’t show signs of plastic deformation, but suffered from damage. Since the late 1960s, welded flange connections were used more commonly than bolted flange connections. After the Northridge earthquake, such a connection is no longer used since most of the damage caused by this earthquake can be mainly attributed to cracking at the bottom beam flange weld, as shown in figure 7 (Nakashima, Roeder, Maruoka 861).

Figure 7. Weld cracking at the bottom of the flange

Source: Earthquake Engineering Research Institute. Crack in steel frame connection. Digital image. *Earthquake Country Alliance*. Southern California Earthquake Center, n.d. Web. 31 July 2017.

Beams under flexural loads result in a tensile force on the welds on the bottom of the flange, which is the cause of the cracking. Aside from weld cracking, column cracking and beam flange cracking also occurred. The damage was typically concentrated amongst new buildings with deeper and heavier beams (Nakashima, Roeder, Maruoka 861-862). This is problematic due to the fact that such beams were designed this way because they were at critical locations of the structure. Similarly, the cracks were found at the bottom side of the beam and the foot of the columns. This type of damage was expected due to similar load paths, however the damage in the CLT members weren't as detrimental to the structure.

In the seismic active zone, structures made of concrete typically included parking structures, hospitals, hotels, and large office buildings. The damage from the 1994 Northridge earthquake can be attributed to the poor connections between the floor and roof diaphragms (Mitchell et al, 376-377). Because of this, there is a lack of adequate load paths for lateral forces and as a result, members fail. Reports found that columns typically failed due to shear failure (figure 8). They also stated failure in gravity columns when paired with ductile members, such as moment resisting frames. Inelastic deformation will happen in the lesser ductile member, which in this case is the gravity column. Gravity columns are meant to only carry “gravity” loads, so it is detrimental when they are used inappropriately for resisting moments. The above results caused shear and tension cracks in the concrete structures.

Figure 8. Shear failure and buckling of column

Credit: Shear failure and buckling in a column at the Holiday Inn, Van Nuys. Digital image.*World Housing Encyclopedia*. Earthquake Engineering Research Institute (EERI) and International Association for Earthquake Engineering (IAEE), n.d. Web. 31 July 2017.

These comparisons were made to show the potential CLT has as a structural material. Its light-weight characteristic helps reduce the damage that may occur during seismic loading. Despite the amplified strength of the Northridge earthquake, the CLT structure proved to stand up against the simulation. It is also important to mention that the discussion developed in this study must be further researched due to the limitations of UC San Diego’s shake table. Since the table can move in one direction (west to east), the results may not be comparable to the actual damage caused by the 1994 Northridge earthquake. Also, the damage discussed and analyzed are only meant for creating a general picture to see how CLT performs in contrast to concrete and steel. It is acknowledged that the different sizes and structural frames will result in different damages. Also, updated codes would also affect the results seen in the test of the specimen.

From this study, the preliminary design performed adequately, showing only minor damages in the diaphragm. Further testing was conducted using different earthquake simulations. Despite testing more earthquakes, the structure showed little to no further damages. Tests show that the structure’s performance is indeed comparable to conventional structural material, such as steel and reinforced concrete. Using the knowledge from this test, a 10-story structure will be designed and tested on UC San Diego’s High Performance Outdoors Shake Table in 2020. By doing further testing, the goal of developing a test-validated methodology for designing tall CLT structures will be achieved.

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