Verification of seismic resistant performance of developed original cross-laminated timber core structure method by shaking table experiment

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Abstract. In recent years, development of wood engineering is gradually increasing. Instead of using many wood columns, cross laminated timber is expected for constructing spacious open space building. Since cross-laminated timber has high rigidity and strength, cross-laminated timber is expected to be used as earthquake resistant wall or floor diaphragm that makes the span of building can be increased and the position of the wall can be adjusted openly. In order to optimize the performance of cross-laminated timber for open space building, original cross laminated timber core structure method was developed. In this paper, the development concept of original cross laminated timber core structure method will be explained. In this method, the joint connection for each element such as joint connection for wall-concrete foundation, wall-beam, and wall to hanging wall was also developed. The experiment to verify the strength and rigidity of each connection has been conducted and the result will be described. The shaking table experiment of 3-story open space building constructed by original cross laminated timber structure using varies earthquake waves was conducted. In this experiment natural period, shear force for each floor, story drift, and building response data is taken. The result shows the structure designed by original CLT core structure method is satisfy the requirement based on Japan cross-laminated panel structure regulation.

1. Introduction
In current era, structure engineering needs to consider the environmental problem for designing the structure. Sustainable design engineering is becoming more important, and is expected to be implemented for many engineering designs. Wood is one of the sustainable materials, and its material
properties has many benefits for structures. Generally, wood has lighter weight compared to other structural materials such as concrete and steel. Besides that, timber structures also have enough strength to resist earthquake loads.

Currently, there are two kinds of engineered wood usually used for structures, glued laminated timber (glulam) and Cross Laminated Timber (CLT). Glulam is made by many layers of wood boards bonded by moisture-resistant structural adhesives. Glulam is usually used for structural columns and beams. CLT is made by layers of lumber glued, with each layer of boards oriented perpendicular to adjacent layers. As we know that wood has more strength in the fiber parallel direction, CLT makes each layer perpendicular to each other so it has enough strength for parallel and perpendicular directions. [1] Since CLT has comparatively high in-plane rigidity, this engineered wood is usually used for structural walls and floor diaphragms.

Timber structures are commonly used for housing, but recently the demand for timber structures for buildings other than housing such as offices, libraries, and open space buildings is increasing. For housing, many partitions are usually used so that columns and structural walls can be put in the partition range. On the other hand, office, library, or open space buildings have less partition, so the columns are not expected to be put in the middle of the area. In this kind of building, CLT is expected to be used.

2. Original Cross-Laminated Timber Core Structure Method Outline

Other than housing, currently timber structures are expected to be applied in offices or other open space buildings. Frame structure methods have many limitations due to less rigidity and strength, so it is very difficult to design large space rooms. To solve this problem, original cross-laminated timber core structures are proposed in this paper.

![Frame Structure Method and Original CLT Core Structure Method](image1)

**Figure 1.** Comparison of frame structure method and original CLT core structure method

![Design of Building Using Original CLT Core Structure Method](image2)

**Figure 2.** Design of building using original CLT core structure method

The main concept is to design the CLT panel as a core structure that will take horizontal loads caused by wind or earthquake. CLT panels will be used as structural walls and floor diaphragms, so the
column and beam only take the vertical load. Using this concept, wall to wall span can be increased so the large open space is easy to be designed. [2] The image concept of original CLT core structure method is shown in Figure 3.

![3D image of original CLT core structure method building](image)

**Figure 3.** 3D image of original CLT core structure method building

### 3. Development of Metal Joint Connection

In original CLT core structure method, CLT wall is the main part of the structure. 100% of horizontal load is expected to be taken by CLT wall. So that the wall will have to transfer shear force to the floor or foundation by the shear joint connection. Due to the horizontal load, CLT wall will also have rocking movement, so tension joint connection is required. In original CLT core structure method, joint connection using metal is developed and the strength is verified by experiment [2].

#### 3.1. Metal joint connection composition

The connection used in original CLT core structure method and each connection composition is mentioned below:

- **Wall-foundation tension metal joint connection**
  
  This connection is made by round steel bar hanger with holes that will be inserted to the CLT wall and pinned by drift pin (φ12mm). The round steel bar hanger will be integrated to the box steel plate by high tension bolt (M20), and the box steel plate will be anchored to the foundation by anchor bolt (M20).

- **Wall-foundation shear metal joint connection**
  
  This connection is made by steel base plate (t=16) and ellipse-shaped steel plate. The ellipse-shaped steel plate will be inserted to the CLT wall and pinned by drift pin (φ12mm), the base plate will be anchored to the foundation by 4 pieces of anchor bolts (M16).

- **Wall-floor shear metal joint connection**
  
  This connection is made by steel plate connected with steel dowel and ellipse-shaped steel plate. The ellipse-shaped steel plate will be inserted to the CLT wall and pinned by drift pin (φ12mm), and steel plate with steel dowel will be inserted to the floor to transfer the shear force.

- **Wall-wall (hanging wall) shear metal joint connection**
This connection is made by U-shaped steel plate. The steel plate will be inserted to the beam or wall and pinned by drift pin (φ12mm), the plate will be connected to the CLT wall by lag screw bolt (M12) and steel bar.

- **Wall-beam shear metal joint connection**
  This connection is made by U-shaped steel plate. The steel plate will be inserted to the beam or wall and pinned by drift pin (φ12mm), the plate will be connected to the CLT wall by steel bar.

![Figure 4. Metal joint connection of original CLT core structure method](image)

3.2. *Metal joint connection experiment results*

To confirm the characteristic and strength of the developed metal joint connection, the experiment of wall-foundation tension joint connection using single and double connection are conducted. In addition, wall-foundation shear connection and wall-floor shear connection are also conducted.
Using the result of metal joint connection experiment, each metal joint connection rigidity and strength is evaluated below.

- **Wall-foundation tension metal joint connection**
  For wall-foundation tension metal joint connection, single used metal joint connection and double used metal joint connection are conducted to check whether the strength of using double used metal connection will be linear or nonlinear. For single used, in around 120 kN the drift pin start yielding and drift pin start compressing the CLT panel and finally the outer part of CLT panel is damaged and the test end.
  For double used metal joint connection, the characteristic is almost same with single used, the yield strength is around 2.0-2.1 times of single used, so it can be concluded that the strength of double used tension metal joint connection is increasing linearly.

- **Wall-foundation shear metal joint connection**
  In this connection experiment, in around 200-250 kN load, CLT panel start cracking and drift pin and steel plate is yielding.

- **Wall-floor shear metal joint connection**
In this connection experiment, in around 100-150 kN, steel dowel and nail connected to the floor panel is bending. Steel plate is yielding but no bending is observed at drift pin.

4. Shaking Table Experiment
To verify the effectiveness and design performance of original CLT core structure method, the specimen of real scale 3-story building is constructed and shaking table experiment is conducted [2].

4.1. Shaking table experiment specimen outline
The specimen of shaking table test is a building that designed with original CLT core structure method. The building specimen has 3-story with maximum height of 9.588 m, rectangular shape of 7.5×7.6 m plan with 171m² is adopted. In the middle of the building CLT core structure is used, in the right and left side of CLT core structure, frame structure made by glulam is used. In CLT core structure, CLT floor made by Japan Cedar Mx60-5-7 (JAS) t=210 mm and CLT wall made by Japan Cedar S60-5-5 (JAS) t=210mm are used. In frame structure part, glulam column made by Europe Red Pine E95-F315 (JAS) with size 120 × 120 is used. In this experiment the load equivalent to apartment house in Japan is adopted. For 3rd floor 3.5 kN/m², for 2nd and 1st floor 5 kN/m² of load are applied. To give the load equivalent with the design load, steel plate and H-beam are used for loading in the specimen.

In this experiment the response of the structure such as structure natural frequency, story acceleration, and story drift are measured.

Figure 7. 3D model of shaking table experiment specimen

Figure 8. Plan view and section view of shaking table experiment specimen
4.2. Excitation load plan

For the excitation load of this shaking table experiment seven earthquake waves are adopted. To check the reliability of the structure, earthquake wave equal to 500 years return period earthquake (BSL18%) and 2500 years return period earthquake (BSL90%) based on Japan Building Standard Law is adopted [3,4]. To understand the performance and behaviour of the structure other waves are also adopted. The list of excitation load plan and each response spectrum are mention in Figure 9.

| Input Earthquake Waves | Max Acceleration (gal) | Remarks |
|------------------------|------------------------|---------|
| JMA Kobe_NS(100%)      | 21                    |         |
| JMA Kobe_NS(100%)      | 234                   |         |
| JMA Kobe_NS(50%)       | 455                   | Return Period 500 years EQ |
| JMA Kobe_NS(50%)       | 692                   | Return Period 2000 years EQ |
| JMA Kobe_NS(25%)       | 395                   | 1.5 Return Period 2000 years EQ |
| JMA Kobe_NS(10%)       | 431                   |         |

Figure 9. Excitation load plan and response spectrum

4.3. Experiment result

The data taken in this experiment are structural natural period, maximum story drift, and story shear force-story drift. As a comparison, the experiment using single used tension joint and double used tension joint is also conducted. The result is presented in 4.3.1 until 4.3.3 subsection.

Figure 10. Double and single used tension joint specimen

4.3.1. structure natural period

After each excitation load, the structure specimen is loaded by random wave in small acceleration to check the structure natural frequency. This natural frequency will be compared to the initial natural period. By comparing the natural period, the damage to the structure can be noticed. The measurement result of structure natural period is shown in Figure 11.
In the first day until third day specimen using double tension joint is tested. The initial structure natural frequency is about 4.1 Hz, after BSL (18%) and BSL (90%) the natural period is almost having no difference. After BSL (135%), the structure natural period drop to 3.4 Hz, means the rigidity of the structure is decreased, and yielding in some part of the structure is noticed. Same tendency come after JMA Kobe NS L2 and JMA Kobe NS (100%). The condition of the structure wall is almost has no damage, structure rigidity decrement is caused by the loose of the tension connection bolt. In the fourth day, specimen using single tension joint is tested. The initial structure natural frequency is about 3.7 Hz, after BSL (18%) the natural frequency is almost having no difference. After BSL (90%) the structure natural period drop to 3.4 Hz, means the rigidity of the structure is decreased and after JMA Kobe NS (100%) the structure natural frequency is largely drop to 3.0 Hz. In Figure 11, the damping ratio is also shown. The damping ratio for the specimen is about 1.9%, while the structure natural period decrease, the damping ratio increase, means there is more energy absorption from yielding in some parts of the specimen.

4.3.2. Maximum story drift
According to Japan CLT panel structure regulation, the maximum story drift for earthquake with 500 years return period is 1/120 to prevent damage to the building, and for earthquake with 2500 years return period is 1/50 to prevent the collapse of the building [5-7]. The maximum story drift of specimen using double tension joint for BSL (18%) and BSL (90%) is less than 1/120. But for JMA Kobe NS (100%), the story drift is over 1/120 but less than 1/50, means the structure is damaged but still not collapsed. The specimen using single tension joint has bigger story drift, but for BSL (18%) and BSL (90%) the story drift is less than 1/120. For JMA Kobe NS (100%) the story drift is over 1/120 and almost reach 1/50, the structure takes big damage and almost collapse. The maximum story drift measurement result is summarized in Figure 12.
4.3.3. Shear force-story drift

For comparison according to Japan CLT panel structure regulation, CLT panel structure shall be designed to resist 0.55g of horizontal load [4,8]. The result of shear force and story drift are shown in Figure 13.

![Figure 12. Maximum story drift measurement result](image1)

![Figure 13. Shear force-story drift graph](image2)

For specimen using double tension joint, in BSL (90%) shear force-story drift graph, the shear force in structure is about 0.55g of horizontal load range, and the graph show linear line, means in this excitation period there is almost no yielding element or decrement of rigidity. In JMA Kobe NS (100%) the shear force in structure is over 0.55g of horizontal load range and the structure story drift does not exceed 1/50 rad, means the structure is still below collapse limit in this excitation period.

For specimen using single tension joint, almost same tendency can be seen, but the larger displacement for the same shear force is confirmed.

5. Conclusion

With original CLT core structure method, larger span and open space timber structure can be more easily designed. The shaking table experiment to test the performance of structure designed by original CLT core structure method shows that the structure is satisfied the Japan CLT panel structure regulation and can resist the earthquake larger than 2500 years return period earthquake.
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