Exploratory study on the utilization of recycled wood as raw material for cross laminated timber

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Abstract. Cross-Laminated Timber (CLT) has been gaining interest in recent years as an attractive and environmental-friendly building material. As such, CLT has been used for structural components in building constructions such as apartments, commercial buildings, or offices. CLT predominantly uses newly harvested lumber as a raw material. In this study, however, CLT fabricated using recycled wood was explored for possible utilization in wood structures. The recycled wood was obtained from wooden boxes, wooden pallets, and scrap wood from lumber suppliers, and their mechanical properties were tested. The average tension-parallel-to-grain strength of these recycled woods was 52.2 MPa, while their average compression-perpendicular-to-grain and compression-parallel-to-grain strength were 20.6 and 4.0 MPa, respectively. Four CLT beams of 2 m-length, 100 mm-width, and 130 mm-depth glued with epoxy adhesive were tested to measure their flexural strengths. A set of two CLT beams was loaded on upright and lying positions, and their average flexural strengths were 8.1 and 7.6 MPa, respectively. The effects of lamina lap splices and adhesives on CLT beam flexural strength were studied. Apparently, adding several variations of lap-splices and adhesives has marginal impact on CLT beam flexural strength.

1. Introduction

Indonesia currently faces several problems relating to environment and forests. One of these problems is deforestation, of which Indonesia has reached an alarming condition (figure 1). It was reported that Indonesia's forest cover is decreasing around 6,840 sq. km annually [1]. Furthermore, the Global Forest Resources Assessments (FRA) of the United Nations Food and Agriculture Organization (FAO) stated that Indonesia ranked the second highest of forest loss (deforestation) among countries in the world, after Brazil took the first place [1].

Among many factors, the high deforestation rate in Indonesia was triggered by the increasing demand of timber every year. In the last 14 years, the timber demand has far exceeded the available quantity of certified timber [2]. The Ministry of Environment and Forestry of Indonesia reported that volume of certified timber from managed forests is 16.17 million cubic meters as of May 2018 [3], 2018), while the amount of wood consumption is 219 million cubic meters [2].
Figure 1. Deforestation condition in Indonesia: (a) map of protected forest cover [4]; (b) aerial view showing deforestation [5]

To alleviate this scarcity of lumber, engineered wood process such as that of cross laminated timber (CLT) products can be applied to manufacture sustainable construction material from reclaimed or recycled wood. The widely known CLT technology has been reported able to improve quality of soft or fast-growing wood to be equivalent to high-quality hardwood products [6, 7]; and CLT products have been applied in many constructions. This research was conducted to examine application of CLT technology on recycled wood, obtained from wooden fruit boxes, wooden pallets, and scrap wood from lumber suppliers, to produce high-quality construction wood.

2. Cross laminated timber and utilization of recycled wood

CLT is an innovative wood product composed of several layers of laminas or thin boards of which each layer is arranged perpendicular to adjacent layers and glued to each other on its wide faces [8]. A typical CLT layer configuration is shown in figure 2. Several advantages of CLT include significant load-bearing capacity and structure stability it can provide to buildings [6, 8]. Also known as X-LAM, CLT generally is arranged in an odd number of layers such as in 3-, 5-, or 7-layer configurations. The dimension of single CLT panel can reach up to 18 m long, 3 m wide, and 300 mm thick, while its lamina varies between 12 to 45 mm thick [9], depending on design requirements and construction needs of certain projects.

Figure 2. Cross laminated timber: (a) typical layer configuration [10]; (b) layers in the minor and major directions [11]

CLT could provide alternative solutions to needs for large-diameter solid sown timber and high-quality timber, which has been increasingly become limited [12]. As a building material, CLT could facilitate design and shape flexibility of buildings [9, 13, 14], is a good insulator to provide energy efficient in buildings [15], has adequate fire resistance [16, 17] and earthquake resistance due to its flexibility and relatively light weight in comparison to concrete or steel materials [18], and is a renewable and sustainable construction material that would help in carbon sequestration and reducing the effects of global warming [13, 19]. CLT products have been implemented to residential buildings,
buildings, offices and industrial buildings in many countries [13, 14] and has been widely applied in structures as bearing walls, floors, roofs, and stairs (figure 3). In addition, CLT also had been utilized in constructions of bridges [20]. Further discussion on the development of CLT research and its implementations are available elsewhere (e.g., [9, 18, 21]).

Figure 3. Application of CLT products: (a) applied as bearing walls and floors [22]; (b) applied as stairs [23]

In addition to laminas as raw materials, adhesive is a key factor to achieve a good quality of CLT products. Adhesive application between layers would create a composite cross section of which its mechanical properties such as stiffness and strength would increase significantly in comparison to that of an individual layer of lamina. Several commonly used adhesives in the manufacturing of wood products include aliphatic based adhesives (samples of marketed brand are Crona 234 and Presto), epoxy adhesives (e.g., Avian Epoxy), PVAc or polyvinyl acetate adhesives (e.g., Crossbond X4 and Titebond III), polyurethane adhesives (e.g., Foam Glue), and cyanoacrylate adhesives (e.g., Super Glue). Initially in this study, epoxy adhesive was used because of its high bond-strength and durability, quick initial tack, tolerable to a wide range of wood moisture content, and low-pressure requirements during curing process [24].

CLT predominantly uses newly harvested lumber as a raw material. In this study, however, CLT fabricated using recycled wood was explored for possible utilization in wood structures. The recycled wood was obtained from wooden boxes for packing fresh vegetables or fruits, wooden pallets to secure fragile goods during shipments, and scrap wood from local lumber suppliers. In the current practice, wooden boxes and pallets, after used several times, are typically disposed to a landfill as waste materials or burn as firewood, which in large quantity both could pollute the environment. Alternatively, these woods could be repurposed by making simple household furniture, shelves or drawers. Based on the idea of seeking an environmental-friendly option for this wood waste through reducing its environmental waste footprint and increasing its valuable usages, this research is aimed to apply CLT technology on recycled wood. Obtained CLT products are expected to be used as floors, beams, columns and load-bearing walls of wood structures.

3. Preparation of CLT beam specimens and experimental setting
The process of preparing specimens started from collecting recycled wood as raw materials obtained from local markets, lumber suppliers, post offices, and fruit sellers around the city of Bandar Lampung (figure 4a). Selected wood, which was relatively in a good condition and undeformed or without cracks, was cleaned from any sticking dirt and sawed afterward to obtain a uniform size (figure 4b). After cutting and sanding all surfaces (figure 4c), one obtained lamina was 40 cm long, 6 cm wide, and 1 cm thick.
Figure 4. Preparation of laminas: (a) piles of recycled wood; (b) processing; (c) processed lamina

Laminas were arranged in 3 layers, as shown in figure 5. At the top and bottom layers, each lamina was arranged in an upright position and resembled brick arrangement along its length. The resulting panel size for each top and bottom layer was 2 m long, 400 mm width, and 60 mm thick. For the middle layer, each lamina was arranged with wide faces perpendicular to the lamina on the upper and lower layers. Thus, a CLT panel of 2 m long, 400 mm wide and 130 mm thick was obtained. After each lamina was adequately glued with epoxy adhesive applied on one side (single spread) of wide face (figure 6a-b), the bottom layer was cold pressed afterward (figure 6c) and left for approximately 3 hours. The same process was repeated for the top layer. The middle layer was installed after the top and bottom layers was completed (figure 6d-f), and the entire layer was pressed for another 3 hours (figure 6g). The resulting CLT panel (figure 6h) was sanded and cut into 4 CLT beams with an approximate size of 2000×100×130 mm (figure 6i) prepared for bending test.

Figure 5. Schematic layout of CLT: (a) top and bottom layers; (b) middle layer; (c) arrangement

Figure 6. Manufacturing of CLT panel: (a)-(b) adhesive application; (c) cold pressing of top and bottom layers; (d)-(e) middle layer instalment; (f) CLT panel; (g) cold pressing of CLT panel; (h) finished CLT product; (i) CLT beams
Meanwhile, tension and compression tests were conducted on recycled wood to obtain its properties. Specimens were prepared from wooden fruit boxes, wooden pallets, and scrap wood. They were tested according to the ASTM standard [25] to obtain tension-parallel-to-grain, compression-perpendicular-to-grain, and compression-parallel-to-grain strengths of recycled wood. The obtained strengths on average were 52.2, 20.6, and 4.0 MPa, respectively. Details about this property tests were available in [26].

Figure 7 shows schematic and test setup for CLT beam 3-point-bending test. The center load at the mid-span of CLT beam was applied by a Universal Testing Machine (UTM) with a displacement control scheme. Two of CLT beams were tested on an upright position (its depth was parallel to the direction of loading) and on a lying position (its width was parallel to the direction of loading). The test was carried out at the Civil Engineering Laboratory of the Universitas Bandar Lampung (UBL).

![Figure 7. Three-point-bending test: (a) schematic of loading; (b) test setup on UTM](image)

4. Flexural strength of CLT beam

Flexural strength of CLT beams can be calculated using the following equation:

$$\sigma = \frac{My}{I}$$  \hspace{1cm} (1)

where $M$ is the flexural moment at the CLT beam mid-span; $y$ is the distance from the center of gravity to the outermost side of the beam, which in this case is half of the beam height; $I$ is the cross section moment of inertia. The maximum moment for the 3-point-bending test can be calculated using the following equation:

$$M = \frac{1}{4}PL$$  \hspace{1cm} (2)

where $P$ is the applied load and $L$ is the CLT beam span length. Note that the self-weight of CLT beam was ignored in this case. Substituting equation (2) into equation (1) and using respective moment of inertia for a rectangular cross section, flexural strength (a.k.a. modulus of rapture, MOR) of CLT beam when tested on the upright and lying positions, respectively, can be obtained using the following equations:

$$MOR_{upright} = \frac{3PL}{2bh^2}$$  \hspace{1cm} (3)

and

$$MOR_{lying} = \frac{3PL}{2hb^2}$$  \hspace{1cm} (4)

where $b$ and $h$ are width and depth of CLT beam, respectively, while other parameters have been previously defined.
5. Discussion of experimental results

5.1. Bending Test of CLT Beams

Figure 8 (a) and (b) show results of the conducted CLT bending test on the upright and lying positions, respectively. A significant drop of load at about 12 mm deflection (figure 8a) occurred when several laminas started to fail, either due to fracture or delamination of laminas. Specimen B1 dan B3 can maintain stability and the remaining laminas able to sustain additional loads prior to a complete failure at more than 40 mm deflection. However, that was not the case for specimen B2 and B4, first failure of laminas occurred at about 15 mm deflection (figure 8b) and progressively lost their capacity to sustain load before a complete failure occurred at about 30 mm deflection. The maximum point load when CLT beams tested on the upright and lying positions reached 5.6 and 4.6 kN, respectively. When failure occurred, CLT beams have deformed 60 and 30 mm for the respective positions, which approximately are 1/30 and 1/60 of CLT beam span.

Table 1 shows a summary of bending test results for all 4 CLT beams tested. Using equation (3) and (4), the average MOR$_{upright}$ and MOR$_{lying}$ are 8.1 and 7.6 MPa, respectively. These results with larger MOR for the upright position compared to that for the lying position are attributed due to the fact that CLT beam’s moment of inertia for the upright position is larger than that of the lying position.

Table 1. Results of CLT Beam Bending Test

| Specimen | Dimension | $L_{span}$ (mm) | Test Position | $P_{max}$ (N) | MOR (MPa) |
|----------|-----------|-----------------|---------------|---------------|-----------|
| B1       | 1998      | 100             | 130           | 12.4          | 1739      | 5557      | 8.58      |
| B3       | 1998      | 85              | 130           | 9.8           | 1744      | 4205      | 7.66      |
| B2       | 1996      | 100             | 130           | 11.3          | 1740      | 4660      | 9.36      |
| B4       | 1999      | 100             | 130           | 11.5          | 1744      | 2913      | 5.86      |

$L =$ beam length; $b =$ width; $h =$ depth; $w =$ weight; $L_{span} =$ beam span; $P_{max} =$ maximum load

Specimen condition during the test is shown in figures 9 and 10 for B3 and B4 specimens, respectively, while that for specimen B1 and B2 are available in [26]. In general, damages were occurred at the interface/connection between adjacent laminas either that along the length or the depth of CLT beam. The damages occurred on CLT beams tested on the lying position (i.e., B2 dan B4) were relatively more severe than that on CLT beams tested on the upright position (i.e., B1 and B3). This observed behavior leads to a further investigation on the effect of lamina lap splices and type of adhesive material used, as discussed in the next sub-section.
Figure 9. Specimen B3: (a) failure condition at the maximum load; (b) slip between layers; (c) failure of laminas (delamination)

Figure 10. Specimen B4: (a) tested on lying position; (b) delamination at the maximum load (facing south); (c) delamination at the maximum load (facing north)

5.2. Effects of lamina lap splices and adhesives

To determine the effects of lamina lap splices and type of adhesive on CLT beam strength, tension-parallel-to-grain tests were conducted on specimens made of three different types of lamina lap splices (i.e., half-, bevel-, and fish-mouth-lap splices) and glued with two different types of adhesive materials (i.e., cyanoacrylate and polyurethane adhesives), as shown in figure 11a. Incidentally, the types of lamina lap splices considered in this research were simple alternatives to a more labor-intensive finger-joint connection. The highest tensile strength of 5.2 MPa was obtained from specimens made of bevel-lap splices and glued with cyanoacrylate adhesive. The strength was approximately twice above that made of the other two lap splices and adhesives. Details about these tests are available in [27].

Figure 11. CLT beam with slap splices: (a) lap splices; (b) bending test

Furthermore, based on the aforementioned tensile strength test, another 4 CLT beams were prepared for bending test (figure 11b). The average \( \text{MOR}_{\text{upright}} \) and \( \text{MOR}_{\text{lying}} \) are 2.7 and 3.4 MPa, respectively. Apparently, adding lap-splices and changing adhesives has marginal impact on CLT beam bending strength. It was probably affected by low pressured applied during the manufacturing process of CLT beams or insufficient glue applied to fill gaps and uneven surfaces between laminas,
especially at the location of splices. Hence, premature delamination was occurred, as observed from the specimen final condition (figure 11b), that consequently lower the CLT beam strength. However, further research would be needed to confirm this initial finding.

6. Conclusions
This paper establishes an initial investigation on the utilization of recycled wood as raw material for cross laminated timber. Flexural behavior of CLT beams was examined and the effect of lamina lap splices and adhesives on CLT beam flexural strength was studied. While the obtained flexural strength was below the ANSI required strength for CLT, yet the result is an essential starting point to guide future investigation on ways to improve its performance. Apparently, applying several variations of lamina lap-splices and adhesives has marginal impact on CLT beam flexural strength.

In this exploratory research, recycled wood obtained from wooden boxes, wooden pallets, and scrap wood, for expediency, were mixed during the manufacturing process of CLT beams. Further investigation is needed to assess how recycled-wood grouping would improve CLT flexural strength. Non-destructive tests could be implemented on piles of recycled wood to select a more uniform strength quality of recycled wood. Impact of assorting wood strength per layer could also be examined. A comprehensive study on lamina splices would be desirable to find simpler alternatives yet could maintain similar connection strength to a finger joint.

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Acknowledgments
Ruri Damayanti, a research assistant at the Department of Civil Engineering of UBL, assisted at the manuscript preparation and layout editing of this paper. Her contribution is greatly appreciated.