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A WORKABILITY AND SUSTAINABILITY ASSESSMENT OF MULTI-STOREY EARTHQUAKE-RESISTANT TIMBER BUILDING

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Masaki Maeda[5]

ABSTRACT: Although two-thirds of the area of Japan is covered with forests, the domestic wood resources are not widely used in the construction sector. Due to the complex design process, construction work and high precision needed, most of timber constructions are limited to one or two-storey buildings. This paper aims to clarify the efficiency of a proposed joint system for CLT walls-steel beams hybrid structure. In addition, the workability and the environmental impact of the proposed hybrid system in comparison to other structures were analysed. The proposed joint system showed higher workability and efficiency compared to other conventional joints in Japan. The construction process of a prototype of a module with the proposed system was studied and confirmed its easier and faster work than the conventional system. A 4-storey building was taken as a case study to evaluate the environmental impact of the proposed system. Although the proposed hybrid system showed higher carbon emissions than a conventional CLT alternative, advantage in terms of the environmental impact was confirmed in comparison to a reinforced concrete and a steel structure.

KEYWORDS: Cross-laminated Timber, Hybrid structure, Workability, Life cycle assessment, Sustainability

1 INTRODUCTION

In recent years, a mid-to-high-rise wooden building has been attracting attention from the perspective of a low-carbon building and the effective use of forest resources. In Japan, although 66% of the total land area is covered by forests (Japanese Forestry Agency (JFA)), these renewable resources are not being used to their full potential. Buildings higher than three stories (mid-to-high-rise buildings) are mainly non-wooden structures [1], with a share of only 0.06% for timber buildings.

Cross-laminated Timber (CLT) is considered a promising engineered wood product (EWP) for a structural material of a mid-to-high-rise building with low carbon emissions. CLT has a similar structural performance as reinforced concrete, which means that CLT has the capacity to resist the weight of the building and large earthquakes. Moreover, recent studies [2-5] found the environmental superiority of mid-to-high-rise CLT buildings compared with reinforced concrete buildings.

However, the common structural systems for CLT buildings have challenges regarding reasonable seismic design and workability. For instance, an unreasonable amount of CLT walls (i.e., to compensate for the low strength and stiffness connections) and a large number of complex connections are needed. In order to tackle the structural challenge, CLT-steel hybrid structures can be a possible solution. The effect of the high strength and stiffness of the steel could be effectively used to increase the CLT panel's capacity under lateral loading, thus reducing the number of CLT panels required. The seismic behaviour of the structure using innovative CLT-steel hybrid systems was investigated by several researchers in the past years [6-8]. Fukumoto et al. [9] theoretically investigated the structural performance of steel frames with CLT infill. They found that the use of steel can increase lateral performance by almost 2.0 times compared to the CLT structure.

Nevertheless, such CLT-steel hybrid structures have a difficulty in workability due to a large number of complex connections. Hence, construction companies struggle to deal with the complex construction due to the hybridization. In addition, studies regarding the environmental performance of the hybrid structure are limited.

This paper proposes a novel hybrid structure with CLT and steel beams with steel joints that are designed to have both high efficiency and workability. Moreover, a case

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study of a building with the proposed system is also introduced (Figure 1) in order to analyse the environmental performance. The targeted building is 4-storey residential building to promote the mid-rise building. The objectives of this paper are 1- Discussing the efficiency and workability of the proposed joint compared to the conventional connections. 2- Demonstrating the workability of the proposed system. 3- Analysing the environmental performance of the hybrid system in comparison to other common structure systems.

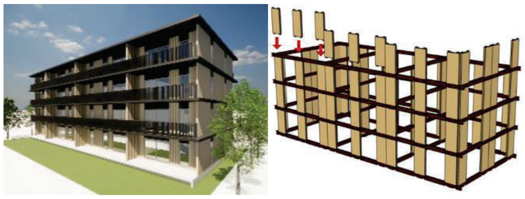

Figure 1: *Targeted CLT walls and steel beams hybrid structure.*

2 PROPOSAL OF A HYBRID STRUCTURAL SYSTEM WITH CLT PANEL AND STEEL BEAM

2.1 Problems of conventional structural systems

In Japan, the ductility of a building is essential to resist earthquakes. Therefore, conventional structural systems are designed to have high ductility. Figure 2 shows the conventional structural systems of CLT panels in Japan. They consist of CLT walls and slabs. The use of CLT slabs caused the reduction of the seismic capacity of the building. When the wall is subjected to lateral force, the wall transfers compression force to the CLT slab perpendicular to the grain, which leads to low rocking resistance.

For the connections of conventional systems, two types of joints are required: tensile joints and shear joints. The tensile joints are installed at the corners of the wall. The common tensile joints are a screw joint with a U-shaped metal bracket and a tensile bolt joint. On the other hand, the shear joints are at the top and bottom of the CLT wall. The common shear joints are a U-shaped and a L-shaped metal connector joint with screws.

These conventional connections have structural challenges. The flexural yielding of screws and the yielding of tensile bolt contribute to the ductility performance of a building. However, although the conventional systems have the desired structural ductility, they do not take advantage of CLT performance to its full potential. For instance, the material's lateral strength of the CLT wall made from Japanese cedar with a thickness of 90 mm (3-ply 3-layer) is reported as 2.31 MPa [10]. Nevertheless, when the tensile bolts are applied as the tensile joints, the strength for designing is 0.40 MPa according to the design guideline of CLT structure [11] This means that the current structural systems utilize only 17 % of the CLT panel performance.

Furthermore, the conventional joint systems have difficulties in material processing and construction workability. The three out of four tensile and shear joint types require Computerized Numerical Control (CNC) processing of the panels for rectangle holes and cut-outs. Making the CNC data and the actual processing in a factory for each CLT panel takes time. Hence, processing CLT wall panels with conventional systems entails higher labour and longer process time.

Regarding the workability of the screw joint, in order to have the necessary structural performance, a large number of screws is required to be installed for 6 joint types. This process takes longer time. As for the tensile bolt joint, anchor bolts are already fixed to the base/floor. Then, the wall is fixed by the anchor inside the pre-drilled holes in the walls. Therefore, high precision for the anchor bolts in the installation is required, which leads to higher labour time and cost.

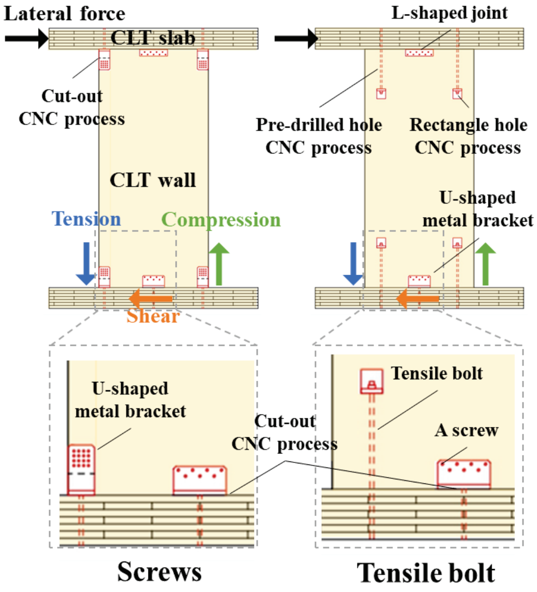

Figure 2: *Conventional structural systems of CLT panels in Japan.*

2.2 Description of a hybrid structural system

To overcome the low efficiency and workability of the conventional systems, a hybrid structure with CLT panels and steel beams is proposed as shown in Figure 3. The use of steel beams increases lateral capacity compared with the use of CLT slabs. Figure 4 shows the differences in the embedment behaviour between the wood slab and the steel beam. The wall transfers compression force parallel to the grain in the main axial layers, which leads to high rocking resistance and better CLT panel performance.

In the joint of the proposed hybrid system configured at the CLT panel corners, steel plates are applied on one side of the CLT panel to connect the panel with steel beams using three bolts in the CLT panel and one bolt in the steel beam. In the proposed structural system, the joint is resisted as the combination of both tension (uplift) and shear forces which are induced by the lateral force applied on the wall. Therefore, the plate joint requires a smaller number of connectors compared with the conventional joints. Regarding processing, CLT walls can be directly shipped from a production factory to a construction site because carpenters can make bolt holes for the walls on site. Hence, the plate joint system can reduce the cost derived from processing. In addition, the construction of materials by bolts does not require a high construction accuracy as opposed to the tensile bolt connection. This makes the installation of CLT walls easier compared to conventional systems.

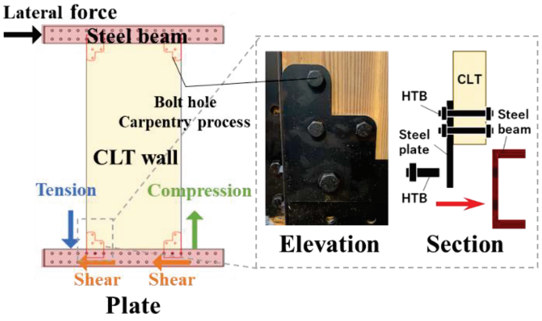

Figure 3: *Details of the hybrid system.*

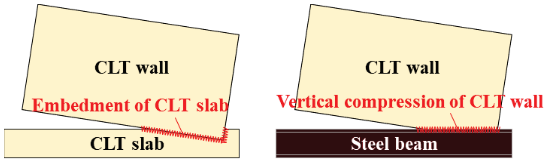

Figure 4: *Embedment difference between a CLT slab and a steel beam.*

3 WORKABILITY PERFORMANCE ANALYSIS

3.1 WORKABILITY COMPARISON

In order to compare the efficiency and workability of the three variations of the joints (two conventional ones and the proposed plate joint), a comparison of the intensity of constructive works of these joints was conducted. The three joints were designed to have the same strength. The design specification and strength of the plate joint were gained from the shear wall tests in a past study [12]. In this study, the joint consisted of three bolts with a diameter of 20 mm (M20), the steel plate with a thickness of 9 mm and the CLT wall with a thickness of 90 mm. The ultimate tensile strength was 66.8 kN. The two conventional joints were designed to have the same strength as the plate joint, based on the design guideline of CLT structure [11]. For the screw joint, the strength of the joint was calculated by multiplying the strength of each screw (5.5 kN) by the number of screws. For the tensile bolt joint, to ensure a ductile failure of the joint, the strength of the joint was calculated based on the yielding capacity of the tensile bolt. In addition to that, the vertical and horizontal edge of the joint (i.e., the distance from the edge of the joint to the edge of the CLT panel) was designed to avoid brittle failure in the CLT wall panel's corner before the tensile bolt yielding.

The specific design and the appearances of the three joints are shown in Figure 5. To have a similar tensile strength with the plate joint, in the case of the screw joint, a U-shaped metal bracket and 12 screws were needed per one corner of the CLT wall, and the thickness of the wall was 90 mm. In the case of the tensile bolt joint, a M20 bolt was needed, and the thickness of the CLT wall was 150 mm to avoid the failure in the CLT wall panel's corner.

As for the screw joint, 48 screws need to be installed per wall for tensile connections, which requires a high workload to drive all necessary screws. The tensile bolt joint required CLT walls whose thickness was 150 mm, which causes a higher production cost. However, in the plate joint, 12 bolts were needed per wall for the connection of the wall and the plate, and the thickness of the wall was 90 mm. In addition, the plate joint required no shear joint. Hence, it was shown that the workability of the plate was better than that of the conventional ones.

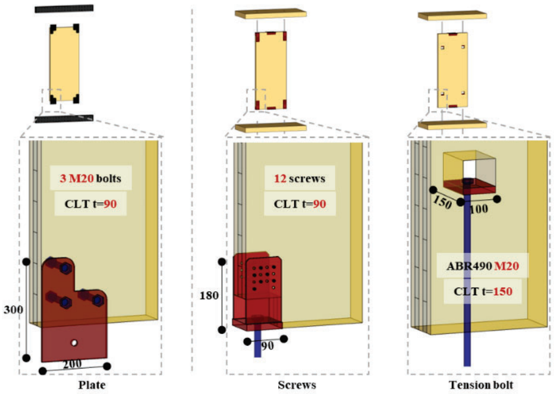

Figure 5: *The specific design and the appearances of each connection that has the same ultimate tensile strength.*

3.2 DEMONSTRATION OF A CLT MODULE WITH THE PROPOSED PLATE JOINT SYSTEM

A module using the proposed structural system with the plate joint was demonstrated to confirm the workability of the proposed joint system. Figure 6 shows a photo and a schematic diagram of the CLT module. The module with a size of 2 m by 4 m in floor plan was constructed for an open-air event in August 2021 in Sendai, Japan. In this event, the module, which housed a small commercial store, contained eight CLT panel walls arranged along the three sides and back of the structure. In Sendai, in the case of the use of local woods, the maximum width of CLT panels is 1.2 m due to the limitation of the production facility of the local manufacturer. Hence, CLT panels with 1 m in width and 2.4 m in length were used as structural walls. The used CLT wall panels were made from Japanese cedar. C-shaped steel section with a 90x200 mm size was used for the beams and the base. For the floor, a wood panel with a thickness of 36 mm was used. For the

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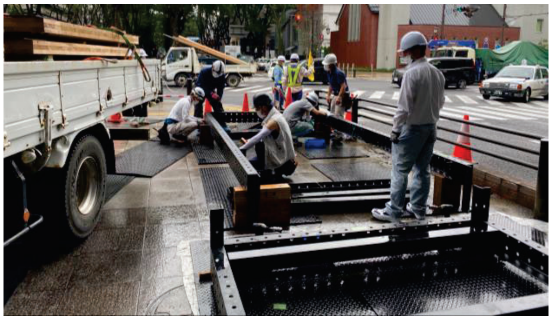
roof, a wood panel with a thickness of 200 mm was applied.

Figure 7 shows the process of the construction work with the following steps: (a) Holes with a diameter of 22 mm were drilled through for inserting the M20 bolts. (b) The steel base and beams were assembled on the ground. (c) For the installation of the CLT walls, two CLT wall panels were splined together in advance by convex shear connectors to increase the efficiency of the construction. (d) The CLT walls were put on the steel base and jointed by bolts. (e) The steel beam frame was installed by a crane. (f) The roofs were constructed by the crane. They were fastened with the steel beams by bolts. (g) Carpenters carried wood panels for the floor by hand and put them on the steel base.

As shown in Figure 8, 173 minutes were needed to finish the construction from (b) to (g). The time required to install the eight CLT panels was about 36 minutes. There was an actual CLT building that was built recently with a conventional joint system. According to local construction experts, 18 to 20 panels can be installed in one day (eight hours of construction time). Thus, the demonstration of the single CLT module indicated better workability compared with the conventional joint system.

Figure 6: *Photo of the CLT module (left); schematic diagram of the module's structural system (right).*

(a) Opening bolt holes for a CLT wall by a carpenter



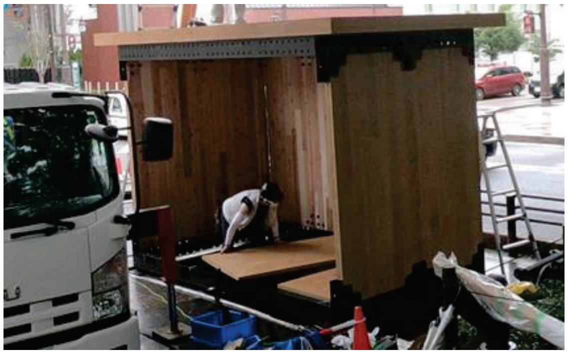
(b) Assembly of the steel base and beams on the ground

(c) Installation of the CLT walls

(d) Jointing the walls and the steel base with bolts

(e) Construction of the steel beam frame

(f) Construction of the roofs



(g) Construction of the floors

Figure 7: *CLT module during construction.*

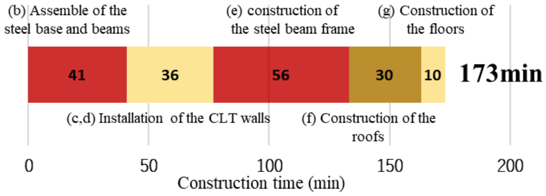


Figure 8: *Each construction time in order.*

4 SUSTAINABILITY PERFORMANCE ANALYSIS

4.1 Target buildings

In order to analyse the sustainability performance of the hybrid structure, a life cycle assessment (LCA) was conducted. The analysis quantitatively compared the environmental impacts among four structural systems, including the proposed hybrid system, conventional CLT, reinforced concrete and steel structures. 4-storey prototype residential buildings with total floor area of 1,000 m^2 were designed in Sendai, Japan. As shown in Figure 9, the structure includes a residential space (8x24 m^2) surrounded by a long corridor and balcony.

4.1.1 Functional unit for structural design

The functional unit was defined as the structural performance margin factor equals to 1. The margin factor of 1 means that the building has the minimum structural safety performance that satisfies the Japanese Building Standards Law (JBSL) regarding structural performance.

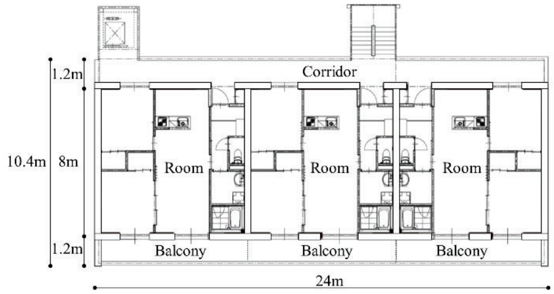


Figure 9: *The image of the floor plan of the 4-storey residential building.*

4.1.2 Building design

In this section, the building design of each scenario is explained. Floor plans and, dimensions and details of structural components were selected to satisfy requirements in JBSL against vertical load and seismic load. Figure 10 shows the floor plans of each building.

The building with the conventional CLT structure (hereinafter CLT building) was designed in the module of 4 m by 8 m. This was because CLT slabs allow spans to be increased up to 4 meters. CLT walls with 1200 mm in width and 210 mm in thickness were used. For the tensile joint, the tensile bolt joint with the diameter of 24 mm was applied. For the floor and the roof, a CLT panel with a thickness of 210 mm was applied according to the design example in the Guidance of Notification of Building Standard Law concerning CLT [13].

Regarding the reinforced concrete structure, two types of structural system are commonly used; moment resisting frame and wall panel structure (hereinafter called “wall type”). In the Japanese design practice, the middle-rise wall type structure is generally selected for residential buildings of reinforced concrete structure. Hence, in this study, the wall type structure was applied for the reinforced concrete structure.

The building with the wall type reinforced concrete structure (hereinafter RC building) was designed in the module of 6 m by 8 m. The floor area is limited up to 60 m^2 in the specification of the JBSL for the wall type structure considering the vibration of slabs. If the module were 8 m by 8 m, an area of one section would have been 64 m^2. Thus, the longitudinal span length was designed as 6 m which gave the same area for four rooms. The RC walls with 1700 mm in width and 250 mm in thickness were used. For the roof and the floor, a reinforced concrete slab with a thickness of 270 mm was applied according to the design example of the guideline for the reinforced concrete [14].

The building with the steel structure (hereinafter S building) was designed in the module of 8 m by 8 m. Steel beams can allow spans to be increased according to the functionality of a building. Therefore, the longitudinal span length was designed as 8 m which gave the same area for three rooms, which can secure larger spaces than the CLT and the RC building. The steel beams with the cross

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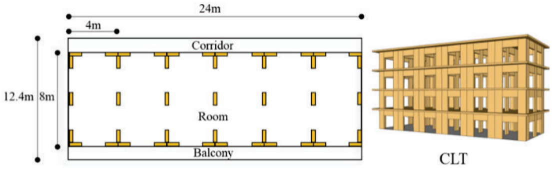
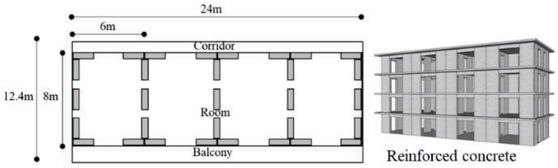
sections of 440x300 mm and the steel columns with that of 400x400 mm was chosen. For the roof and the floor, a reinforced concrete slab with a thickness of 104 mm was applied according to a catalogue of a deck plate company.

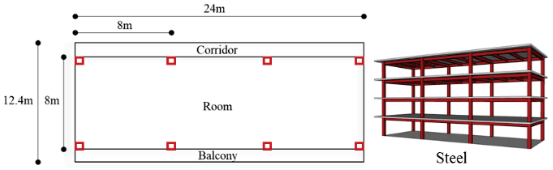
The building with the CLT walls-steel beams hybrid structure (hereinafter CLT+S building) cannot be designed based on the current JBSL. This is because it does not include specifications regarding new hybrid structures. In order to make a reasonable design, the ductility factor was assumed to be between the values of the CLT and S building. As a result, the CLT+S building was designed in the module of 8 m by 8m. Compared to the CLT building, the steel beams allow longer spans. In addition, the needed quantity of CLT walls was decreased from 49 t to 19 t thanks to the hybridization. Compared with the S building, the steel beams could be smaller from the cross sections of 440x300 mm to that of 294x200 mm. This is because the weight of CLT slabs is smaller than that of RC slabs. In addition, putting CLT walls on beams leads to shorter spans that are crucial to bending stress to beams. For the floor and roof, a CLT panel with a thickness of 210 mm was applied according to the design example in the Guidance of Notification of Building Standard Law concerning CLT [13].



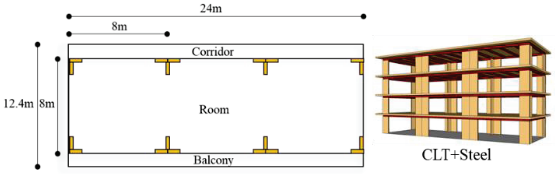
The floor plan and the image of the CLT building.



The floor plan and the image of the RC building.



The floor plan and the image of the S building.



The floor plan and the image of the CLT+S building.

Figure 10: *The floor plan and exteriors of each structure (not considering the foundation).*

The plate joint system of the CLT+S building was improved from the previous one (Figure 3) to correspond with the 4-story buildings as shown in Figure 10. An insertion plate was used to fix two CLT wall panels together using four large diameter high-tensile bolts. A bolt diameter of 30 mm was chosen to have larger embedment strength compared to that of 20 mm. The insertion steel plate with a thickness of 22 mm was designed not to fail. Because C-shaped beams are not available in large sizes in Japan, H-shaped steel beams whose flanges were partially removed were used to accommodate the CLT panel.

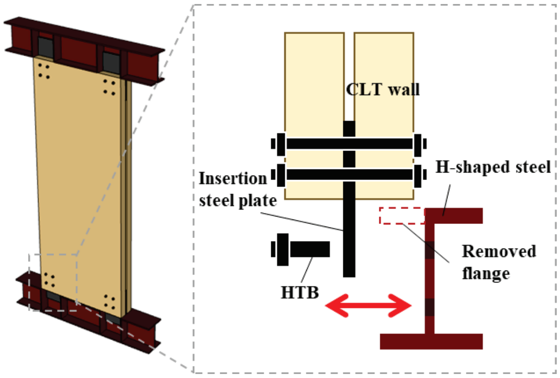


Figure 11: *The specification of CLT walls-steel beams of the hybrid system.*

4.1.3 System boundary in LCA

The life cycle of a building can be divided into material production, transport, construction, use/repair, and demolition/disposal phase. In this study, material production and transport phases were considered in the system boundary to analyse differences by structures. Construction, use/repair, demolition/disposal were excluded for the following reasons. According to [15] and [16], environmental loads during construction are under 1 % of whole emissions. Therefore, ignoring this phase does not make a significant difference. The loads in the use/repair phase are highly dependent on a user of a building. Hence, differences by structures are expected to be small. The data regarding demolition/disposal lacks accuracy because CLT is a new material and most of the buildings with CLT structure are yet to reach their service life.

Wood by-products (wood offcuts and wood shavings) are generated by the pre-cutting of wood laminae and CLT panels. According to an interview with local manufacturing companies, the yield rate from cedar log to wood laminae is almost 50 %. The yield rate from the CLT master panel to the pre-cut panel is approximately 90%. The by-products are used as a heat source for drying cedar lamina, which are the raw material for CLT. It was assumed that the GHG emissions resulting from this drying process are included in the emission intensity value according to Nakano et al. [17].

According to local construction companies, the volume of margin fresh concrete is adjusted to be as small as possible because the disposal of hardened concrete takes additional money. Hence, the concrete residue was assumed to be negligible.

Steel by-products are generated in a process factory. They are shipped to recycle factory and reuse them into other steel products. In this study, environmental impacts regarding the reuse of the steel by-products were out of the boundary.

4.1.4 Inventory analysis

To evaluate the environmental loads, GHG (Green House Gas) emissions and carbon storage were selected as the impact indicators.

GHG emissions at the material production phase were calculated by multiplying the material weight by the intensities of each material. Table 1 shows the weight of each material. For the intensities of steel and concrete, IDEA version 3.1 (National Institute of Advanced Industrial Science and Technology; Sustainable Management Promotion Organization) [18] was applied. Because it does not contain the intensity data of CLT, it was derived from the work by Nakano et al. [17]. Regarding steel production, the most common manufacturing method in Japan was assumed for each product. Specifically, the blast furnace method was assumed for shaped steel and steel plates, and the electric furnace method was assumed for rebars.

Regarding concrete intensity data, the GHG emissions by production and shipment of cement and aggregate are included in the intensity data of concrete according to IDEA v3.1.

Transport distances of each material were decided by discussing it with local construction companies. The distances of concrete, CLT and steel (including joints, bolts, and rebars) were assumed to be 6.4 km, 50 km, and 192 km respectively. The distances were based on the local market situations around Sendai. The GHG emissions by each return way shipment were calculated by considering the impacts emitted by vehicle with no load from a construction site to a manufacturing factory. Vehicles for concrete, CLT and steel shipment were assumed as the 4-t pomp car, the 10-t track, and the 10-t track respectively. The intensities of the vehicles were applied from IDEA v3.1. Because IDEA v3.1 does not contain the intensity data of the 4-t pomp car, the intensity data of the 4-t track was applied.

Carbon storage was calculated using the following Equation (1) based on "the Guidelines for the Indication of Carbon Storage in Wood Used for Buildings" in Japan [19].

$$C_s = W \times D \times C_f \times \frac{44}{12} \qquad (1)$$

where C_s is carbon sequestration of wood used in a building (t), W is the quantity of wood used for building (m^3) (value of air-dried lumber volume), D is the dry density of wood (t/m^3), C_f is carbon content of the wood (-).

Table 1: *Summary of the materials assessed in the study.*

The CLT building

CLT building

Materials			Quantity [t]
CLT wall		1200x2790x210	4.94x10
CLT lintel		895x2000x210 (X-direction) 895x2290x210 (Y-direction)	2.80x10
Tension bolt		Diameter equals to 24 mm	2.92
U shear plate	L shaped	Thickness equals to 4.5 mm	3.78x10^{-1}
	Screw	22 screws per the plate	8.40x10^{-3}
L shear plate	L shaped	Thickness equals to 4.5 mm	5.51
	Screw	33 screws per the plate	2.41x10^{-2}
Shear plate	Plate	Thickness equals to 6 mm	5.76x10^{-1}
	Screw	48 screws per the plate	6.36x10^{-2}
CLT slab		Thickness equals to 210 mm	8.68x10

The RC building

Reinforced concrete building

Materials			Quantity [t]
RC wall	Concrete	1700x2800x250	3.25x10^{2}
	Rebar		4.83x10^{2}
RC beam	Concrete	250x450	3.25x10
	Rebar		4.83
RC slab	Concrete	Thickness equals to 270 mm	4.76x10^{2}
	Rebar		7.07x10

The S building

Steel building

Materials			Quantity [t]
Column		□-400x400	4.62x10
Girder		H-440x300	3.56x10
Beam		H-350x175	8.54
RC slab	Concrete	Thickness equals to 104 mm	2.29x10^{2}
	Rebar		3.40x10
	Deck plate		1.70x10
Exposed column base			1.54

The CLT+S building

CLT+Steel building

Materials		Quantity [t]
CLT wall	1200x2706x180	1.93x10
Plate	300x550x22	8.29
HTB	Diameter equals to 30 mm	1.78
Girder	H-294x200	1.75x10
Beam	H-250x125	5.29
CLT slab	Thickness equals to 210 mm	8.67x10

4.2 RESULTS AND DISCUSSION

Figure 12 shows the results of GHG emissions and carbon storage of each building per square meter of the total floor area. GHG emissions of the CLT building, the RC building, the S building and the CLT+S building were 118 kg-CO_{2eq}/m^2, 268 kg-CO_{2eq}/m^2, 308 kg-CO_{2eq}/m^2 and 143 kg-CO_{2eq}/m^2 respectively. Carbon storage of the CLT, CLT+S building were 225 kg-CO_{2eq}/m^2, 156 kg-CO_{2eq}/m^2. The results showed that the CLT+S building emitted higher GHG emissions than the conventional CLT alternative and lower than the RC and S buildings.

Regarding GHG emissions of the CLT+S building and the S building, the emissions by the girder of the CLT+S building (42 kg-CO_{2eq}/m^2) was almost half of that of the S building (83 kg-CO_{2eq}/m^2). The smaller size of steel

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beams thanks to putting the CLT walls on the beams significantly reduced GHG emissions.

Regarding the GHG emissions of the CLT+S building and the CLT building, the hybridization reduced the emissions of the CLT wall and the connections (35 kg-CO_{2eq}/m^2) compared with those of the CLT building (64 kg-CO_{2eq}/m^2). However, the additional GHG emission by the steel girders and the beams resulted in larger whole emission of the CLT+S building. From an economical point of view, the current material cost of CLT is very high in Japan. The weight of the CLT walls of the hybrid system (19 t) were one third of that of the CLT building (49 t) thanks to the hybridization. Hence, the reduction of the CLT wall's weight could result in lower production cost.

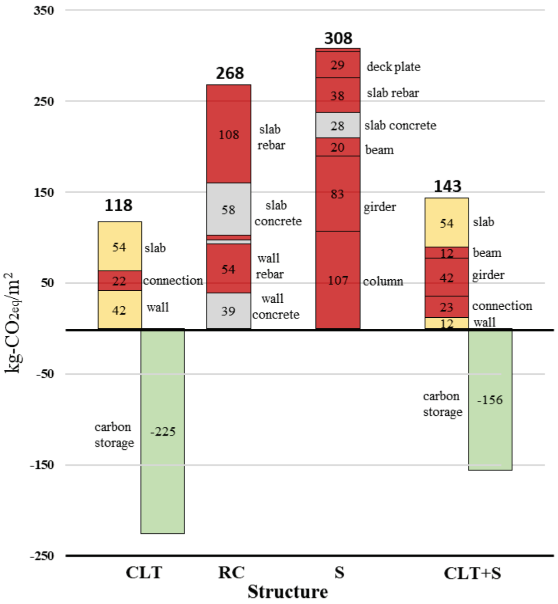

Figure 12: GHG emissions and carbon storage of each building.

5 CONCLUSIONS

In this paper, the efficiency and workability of a new hybrid structural system with CLT walls and steel beams with steel plate joints was introduced. Moreover, the environmental impact analysis of 4-storey buildings with four different structural system scenarios was discussed. The conclusions are as follows:

1. To compare the efficiency and workability of the proposed steel plate joint, conventional screw joint and tensile bolt joint, a comparison of the intensity of constructive works of these joints was conducted. It was shown that the workability of the plate joint was better than that of the screw joint and the tensile bolt joint thanks to the reduced construction processes and a lower precision target.
2. A CLT module with the proposed joint system was demonstrated to confirm the workability. The construction of the proposed system was found to be faster and easier than conventional structural systems. This showed the advantage of the workability of the hybrid system and the steel plate joints.
3. To analyse the sustainability performance of the hybrid structure, a LCA study was conducted. The analysis quantitatively compared the environmental impacts of four different structural systems, including the proposed hybrid system, conventional CLT, reinforced concrete and steel structures.
   As a result, the proposed hybrid system showed higher GHG emissions than a conventional CLT alternative and lower than a reinforced concrete and steel alternatives.
4. The weight of the wall panels of the hybrid system were one third of that of the CLT alternative owing to the hybridization. The current material cost of CLT is very high in Japan. Hence, the reduction of the CLT wall's weight could result in lower production cost.

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