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Developments of Fire-Resistant Wooden Structural Components and Those Applications to Mid- to High-Rise Buildings in Japan

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Abstract

Based on past experiences of natural disasters and fires in Japan, it is stipulated by law that fire-resistant buildings larger than a certain size should be unique in the world. Recent interest in global environmental issues has led to the active introduction of wooden buildings also in Japan, and it is expected that wooden buildings will become larger and higher in size. This paper introduces the background of the development of fire-resistant laminated timber with a "Self-Charring-Stop layer", the contents of this development including other related developments, and the application of these technologies. In addition, towards the realization of much larger and higher buildings in the future, the current problems and issues to be solved are set and the necessity of the future technological development is described. Finally, a conceptual model of wooden high-rise building is proposed, which will be able to be constructed in 2025 by the further technological development.

Keywords: Fire-resistant laminated timber, Cross Laminated Timber (CLT), Wooden beam-column joint, Hybrid structure, Earthquake-resistant CLT wall

1. Introduction

In the past most buildings in Japan were made of wood. Wooden buildings in urban areas have been severely damaged by natural disasters such as typhoons, huge earthquakes like the Great Kanto Earthquake, and large-scale fires after earthquakes. The Building Standards Law, enacted in 1950, prohibited the construction of wooden buildings larger than a certain size in urban areas to prevent damage to wooden buildings and to protect forest resources that were depleted after World War II.

In recent years, however, expectations for the construction industry regarding climate change control have been increasing due to concern over global environmental issues, and the active introduction of wood-based architecture has become a global trend.

Many urban areas in Japan are designated as fire prevention areas, so that fireproof buildings are essential except for small-scale detached houses. It is required that the fire-resistant structural member used for the fireproof building can support the dead load even after the prescribed heating time. In 2000, the Building Standards Law was revised to specify the performance of wooden buildings in order to meet the diverse requirements for wood-based buildings and their continuous development, and wooden buildings became possible to be treated as fireproof buildings by satisfying the prescribed fireproof performance. Based on this background, the "Act on Promotion of Utilization of Wood in Public Buildings" was enacted in 2010 to promote the utilization of wood in buildings in Japan. In the future, the number of wooden buildings will increase in urban areas, and the scale of the buildings will become larger and higher. This paper reports the development of fire-resistant laminated timber for fireproof buildings unique to Japan and its application to mid- to high-rise wooden buildings.

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2. Development of Fire-resistant Laminated timber (1-hour fire resistance)

2.1. Development Goals and Issues to be Resolvedequations

The purpose of this technology development was to realize the structural members (: columns and beams) of laminated timber with fire-resistant performance that can be used while its surface being revealed. The structural members of wooden buildings have been used while those surface being exposed without covering with finishing materials since ancient times in Japan, so when wooden materials are used, a space where one can feel the natural scent and warmth of wooden materials is often required. Therefore, there is a strong need to reveal wooden surface as much as possible when using wood materials.

Examples of fire-resistant laminated timber to give fire resistance to laminated timber include "membrane type", which covers the surface of laminated timber with incom-

bustible gypsum board, "steel-hybrid type", which covers steel members with laminated timber as a substitute for fireproof coating of steel members, and "chemical-treatment type", which covers its surface with laminas that have been treated with chemical agents to prevent flammability. However, in the "membrane type", the fireproof layer is made by covering it with gypsum board, so it is impossible to use the wood while its surface being revealed. In addition, the main structure with the "steel-hybrid type" is steel-framed and not wooden structure from the first. On the other hand, the "chemical-treatment type" had many problems in securing the adhesive strength of chemical-treated lamina, establishing the quality control method during chemical treatment, and securing the fire-resistant performance after aging. In view of the above, it has become essential to develop fire-resistant laminated timber with "Self-Charring-Stop layer" that can be used with its surface revealed.

The fire-resistant laminated timber with the "Self-Charring-Stop layer" was made of bonded glued laminated timber (: wood that has not been chemically treated), consisting of a center "load-bearing part", an outer "Self-Charring-Stop layer", and a surface "combustible margin layer". In order to realize the fire-resistant laminated timber with the "Self-Charring-Stop layer", it was decided to solve problems by setting target performances and various countermeasures.

2.2. Development Process

2.2.1. Development of Wooden Structural Components with 1-hour Fire Resistance

Various methods and material combinations have been studied to ensure excellent structural performance and sufficient fire resistance, and to improve the fire resistance of laminated timber. The cross section of the developed fire-resistant laminated timber is composed of three layers. The three layers are the outer "sacrificial layer", the middle "Self-Charring-Stop layer", and the center "load-bearing part" (Fig. 1). The outer "combustible margin layer" is the layer that will carbonize in the event of a fire, and has a heat shielding effect and an effect of reducing heat inflow to the inside. The intermediate "Self-Charring-Stop layer" stops the propagation of combustion by

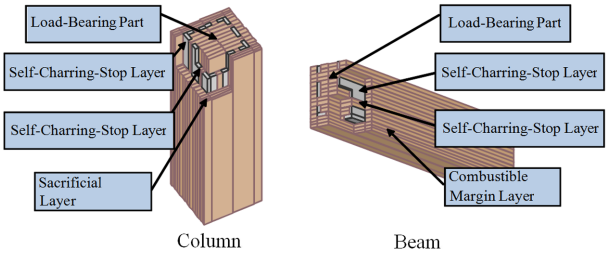


Figure 1. Illustration of fire-resistant laminated column and beam: Moen-Wood (patented).

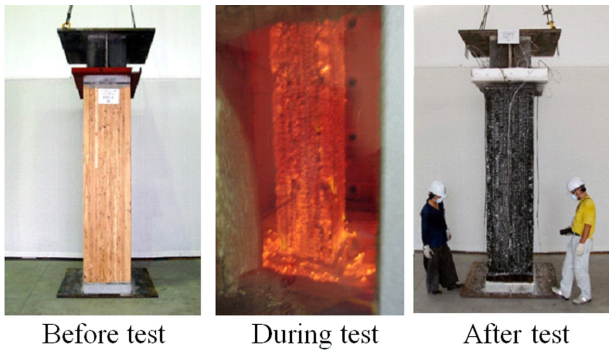


Figure 2. Fire resistance certification test.

absorbing the thermal energy of "sacrificial layer" and continues self-combustion after the end of the fire. This "Self-Charring-Stop layer" is made of a material with a large heat capacity or a material capable of efficiently blocking heat from entering the "load-bearing part". The role of the center "load-bearing part" is to safely support the building weight after a fire.

Regarding the material selection and arrangement of the "Self-Charring-Stop layer", the performance confirmation experiments were repeatedly carried out. As a result of various tests, it was found that "stop combustion" was possible by alternate arrangement of wood and mortar, high-density wood and incombustible wood. In addition to the results of the above combustion tests, several other conditions, such as productivity, quality control, and fabrication costs, were taken into account to finalize the specification for an alternative arrangement of mortar and wood from the test of "heat-capacity type". Based on these specifications, both the larch and cedar cases were approved by the Minister of Land, Infrastructure, Transport and Tourism as laminated timber columns and beams for 1-hour fire resistance, which are structural elements (Fig. 1).

After the fire resistance test, the individual test pieces were taken out from the "load-bearing part" of column and beam, and the vertical loading test was carried out, and it was confirmed that the stiffness and strength of "load-bearing part" were larger than those assumed in the structural calculation, or the criteria defined in the Building Standard Law. During the fire resistance test, the outer "combustible margin layer" did not separate or fall off from the "load-bearing part" (Fig. 2).

2.2.2. Development of Beam-column Joint

The development of beam-column joints began with the determination of the structural framing system of the building. In order to fully bear the seismic force in a structural frame consisting of columns and beams using laminated timber, a joining method with high rigidity and load-carrying capacity is required, but it was anticipated that the mechanism of the joints would become very complicated to realize the joints with required structural performance inside the fire-resistant layer of laminated

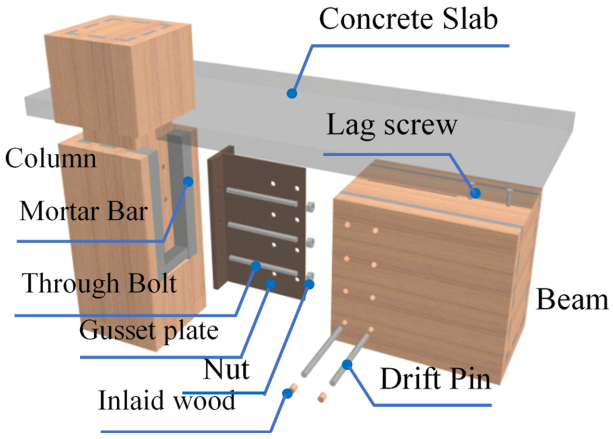


Figure 3. Illustration of beam-column joint.

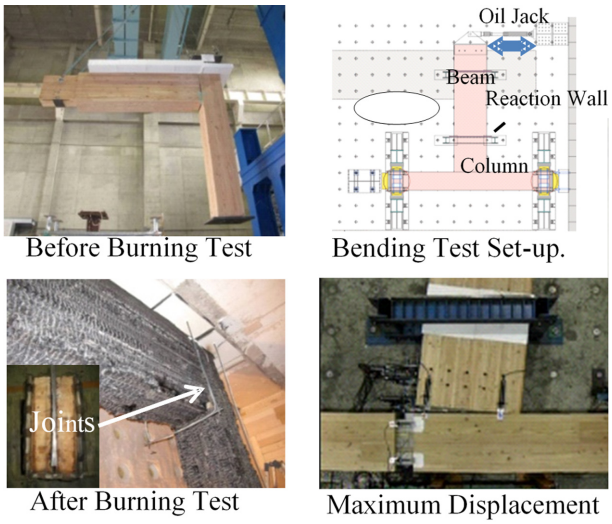


Figure 4. Combustion test and bending test of beam-column joint.

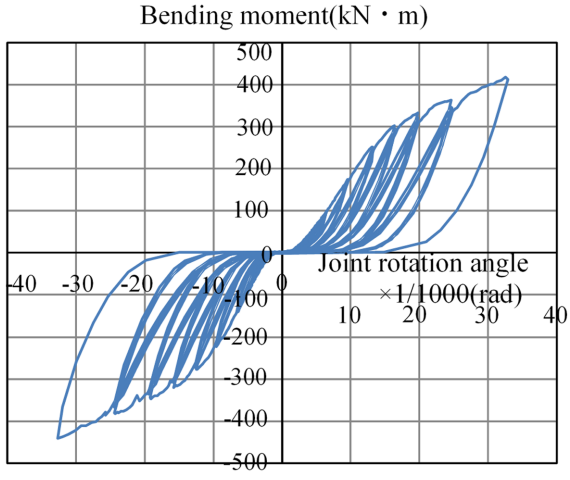


Figure 5. Bending test results of beam-column joint.

timber. Therefore, the structural frame is a hybrid structure of fire-resistant laminated timber and steel or reinforced concrete, and all horizontal forces due to earthquakes, etc. are borne by steel or reinforced concrete, and the fire-resistant laminated timber supports only dead load, thus simplifying the joining method.

Even if the joining method is simplified, it was necessary to consider the heat transfer to the "load-bearing part". In the event of a fire, the gap between the column and beam caught fire, exposing the joint metal to fire and transmitting heat to the "load-bearing part" was a major concern. A jointing method which prevents excessive deformation on the joint part and safely transmits stress between the column and the beam is required, while ensuring fire resistance of a beam-column joint for one hour. In order to meet these performance requirements, a jointing method was developed as shown in Fig. 3.

A T-shaped gusset plate is fastened to the side face of the column by passing a bolt through "load-bearing part" of the column. The space between the "load-bearing part" of the column and the gusset plate is surrounded by mortar-bars composing "Self-Charring-Stop layer" and this space is filled with rock wool excellent in fire resistance. The gusset plate sticking out from the column is inserted into a vertical slit provided in the "load-bearing part" of the beam, and drift pins are inserted from a side surface of the beam to be fastened. Finally, the holes and gaps at the beam-column joint were each finished with inlaid wood (Fig. 3).

Bending test and fire resistance test for one hour were carried out to confirm the structural and fire-resistant performance using this joint system for the full scale test specimen. In the presence of a public performance evaluation organization as a third party, a fire resistance test of a full-scale specimen while applying a vertical load was carried out, and it was confirmed that the beam-column joint had fire resistance for one hour (Fig. 4). As for the structural performance of the beam-column joint, in the bending test using the full-scale test specimen, it was confirmed that sufficient safety could be secured because of the deformation behavior with high ductility even if large rotational deformation occurs in the beam-column joint due to horizontal force caused by seismic force (Fig. 5). In addition, it was also confirmed that even if a large rotational deformation occurred at the beam-column joint, the "combustible margin layer" and the "Self-Charring-Stop layer" were joined without separation or falling off.

2.2.3. Development of Fireproof Compartment Walls and Perforated Beams

In the portion where the fireproof partition wall and the fire-resistant laminated timber are combined, the "combustible margin layer" burns, and a gap is formed in the joint portion with the fireproof partition wall. In order to prevent this gap, a combustion experiment using a foamed

material at the joint was carried out. In the experiment on the fireproof partition wall, it was confirmed that fire did not pass through the opposite side of the wall and that the wall had fire resistance for one hour.

In order to transfer heat from the inside of the hole to the "load-bearing part" of the perforated beam, combustion experiments were carried out using the "Self-Charring-Stop layer" made of mortar and foamed materials in the same way as the joint of the fireproof partition wall. From the experimental results, it was confirmed that "load-bearing part" has fire resistance for one hour. In addition, a bending test of the perforated beam was conducted, and the structural strength required for structural design was confirmed, and the effect of the hole on the structural performance was grasped.

2.2.4 Other Relevant Development Issues

A number of other problems have been solved in the construction of buildings using the fire-resistant laminated timber with the "Self-Charring-Stop layer".

In the manufacturing stage, a manufacturing technology for joining wood and mortar in the production of fire-resistant laminated timber was established, which had not been experienced before. In addition, because of the hybrid structure with reinforced concrete, a construction method to prevent the surface of wood from getting dirty during construction was developed for concrete as the strong alkaline material.

The maintenance and repairing standards of buildings after completion have been improved. During the service life of the building, the crack of the wooden material is an unavoidable problem due to its nature, but the allowable crack width was derived based on the combustion test of the full- scale test piece in order to grasp the effect on the fire resistance performance.

3. Application of 1-hour Fire-resistant Laminated Timber to Low-rise Buildings

The 1-hour fire-resistant laminated timbers with the "Self-Charring-Stop layer" have been used for large-scale wooden buildings since 2012. Two buildings that were the first to be applied are introduced.

3.1. Osaka Timber Association Building

3.1.1. Building Outline

- Design and supervision: Takenaka Corporation
- Building site: Osaka
- Building function: office
- Total floor area: 1,032 m^2
- Building scale: 3 floors above ground
- Structure: Earthquake-resistant, wooden and reinforced concrete structure

3.1.2. Outline of Structural Design

This project is a reconstruction plan of the hall of the cooperative association which has a history of dealing with wood, and this building aims to become an information transmission base of wood utilization in urban areas (Figs. 6 &7).

The conceptual framework of this building is shown in Fig. 8. The first story is made of reinforced concrete against the tsunami damage, and the second to third stories are made of wood and reinforced concrete. The wooden frames cover about 50% of the total floor area. The wooden frame is arranged only in one direction, and the simplification of the beam-column joint and the continuity between the ceiling and eaves are ensured. The reinforced concrete frames are concentrated in the core and bear all horizontal forces.

3.2. Southwood

3.2.1 Building Outline

- Architectural design and supervision: Yukiharu Takematsu & EPA
- Structural design: Takenaka Corporation
- Building site: Yokohama, Kanagawa
- Building function: Retail / office
- Total floor area: 10,874 m^2
- Building scale: 4 floors above ground and 1 floor below ground
- Structure: Earthquake-resistant, wooden & reinforced concrete structure



Figure 6. Osaka Timber Association Building; Outside view.



Figure 7. Osaka Timber Association Building; Inside view.

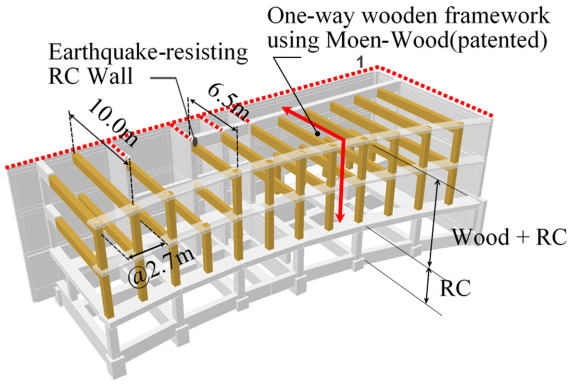


Figure 8. Osaka Timber Association Building; Perspective of skeleton.

3.2.2. Outline of Structural Design

This building was planned as a large-scale commercial facility that can contribute to the community by actively utilizing "wooden materials" aiming at environment-friendly architecture. Tenants also use wooden interior designs that harmonize with fire-resistant laminated timber columns and beams. As a structural plan, three stories of the second to fourth floors, which require 1-hour fire resistance, were made into a hybrid structure of fire-resistant laminated timber and reinforced concrete, and the first story, which requires 2-hour fire resistance, was made of reinforced concrete structure (Figs. 9 &10). The wooden frame is arranged in an interval of 4,500 mm and supports the dead load. The maximum span of fire-resisting laminated timber beam is 9 m, and the technology of perforated beam was adopted for this beam. Rein-forced concrete frames are arranged in the core and its periphery, and all horizontal forces are borne by these reinforced concrete frames.



Figure 9. Southwood; Outside view under construction.

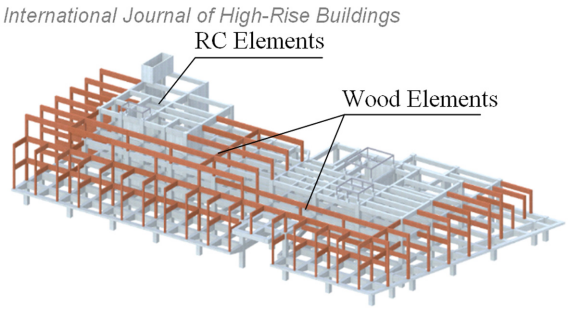


Figure 10. Southwood; Perspective of skeleton.

4. Development of Fire-resistant Laminated Timber (2-hour fire Resistance)

4.1. Development Goals and Issues to be Resolved

Since the development of 1-hour fire-resistant laminated timbers with the "Self-Charring-Stop layer" in 2012, there has been a growing public interest in wooden buildings, and there is a growing need to increase the possibility of using wooden materials in urban areas and a requirement of the technological development for fireproof wooden structures applicable to mid- to high-rise buildings as well. In order to ensure the safety of large-scale buildings in the event of a fire, it became necessary for wooden or woody buildings to have the same fire protection and fireproof performance as reinforced concrete or steel-framed buildings.

In the Building Standards Law, the required fireproof performance is decided by the number of stories and structural parts. One-hour fire-resistant wooden members used for columns, beams, and floors are limited to four-story buildings or buildings with wooden structures up to four stories from the top floor. 2-hour fire-resistant materials for columns and beams can be applied to mid- to high-rise buildings with 14 stories, and 3-hour fire resistance is required for buildings with 15 stories or more. It should be noted that floors in the building with 15 stories or more can be used as long as they have a 2-hour fire resistance (Table 1).

4.2. Development Process

4.2.1 Development of Wooden Structural Components with 2-hour Fire Resistance

In order to secure the fireproof performance, it was decided not to change the three-layer composition of "combustible margin layer", "Self-Charring-Stop layer", and "load-bearing part" in the same way as the conventional 1-hour fire-resistant laminated timber. However, in order to secure the fire resistance which is a major issue, the

Table 1. Target items for 2-hour fire-resistant performance

Structural Element	Material	Tree Species	Limit of Building Stories
Colum and Beam	Laminated Timber	Cypress, Larch and Cedar	Less Than 14
Floor Slab	Cross Laminated Timber	Cedar	None

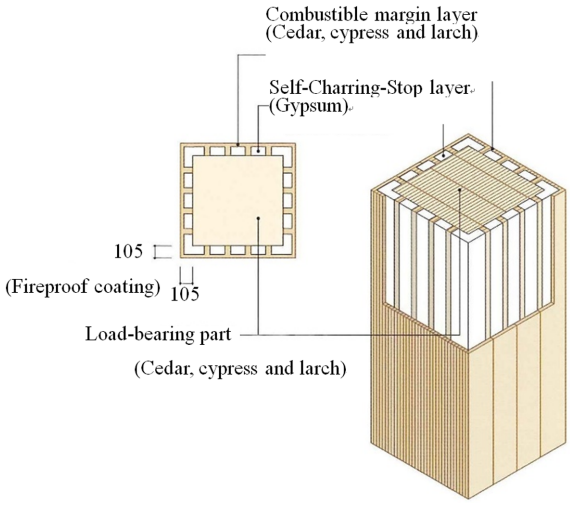


Figure 11. Illustration of 2-hour fire-resistant laminated timber.

mortar used for the "Self-Charring-Stop layer" was changed to gypsum with excellent fire resistance, and it was decided to develop and put into practical use as a wooden member which can withstand a fire for two hours. (Fig. 11)

The mechanism to stop the burning of this timber is that the "combustible margin" of the outermost layer of wood burns slowly and forms a carbonized layer to suppress the penetration of heat, and the gypsum of the "Self-Charring-Stop layer" absorb the heat generated by the combustion, thereby creating a situation in which the "load-bearing part" of timber does not exceed the combustion and carbonization temperature of 260°C (Fig. 12). In the development of 2-hour fire-resistant wooden member, fire-resistance experiments were conducted under extremely severe conditions, it was confirmed that the developed laminated timber had sufficient performance for the target criteria.

In the experiment using a test specimen with a length of 6,000 mm as heating range, a "combustion margin layer" of 30 mm and three zones of "Self-Charring-Stop layer" with 55 mm, 65 mm, and 75 mm in thickness of the gypsum, heating was performed according to a predetermined heating curve for 2 hours, and then the test specimen was left for 24 hours. The experimental results showed that "load-bearing part" did not reach 260°C in any thickness of the "Self-Charring-Stop layer", which indicates the carbonization of the wood (Figures 13, 14). From the experimental results, in order to create a situation in which combustion does not occur in the "load-bearing part" even under variable environments, the thickness of the "combustible margin layer" and the "self-charring-stop layer", which corresponds to the fireproof coating, was set at 105 mm (with the 75 mm gypsum) against 85 mm for 1-hour fireproof.

4.2.2. Development of wooden structural components (floor slab) with 2-hour fire resistance

In developing floor slabs with fire-resistant performance, it was pointed out that the floor to be developed has not only structural performance and fire-resistant performance but also various functions required for boundary floor such as sound insulation, water shielding and odor interception, and good workability.

Four gypsum boards with a thickness of 15 mm were pasted on the bottom surface of the slab to make a total of 60 mm fireproof layer, and the upper surface was used for a fireproof layer into which gypsum (named "SL-Plaster-SK") was poured in the same way as columns and beams (Fig. 15). Meanwhile, by pouring gypsum on the floor surface and hardening it, it is made to have water shielding and deodorization performance which are required performances of the floor. The thickness of the gypsum was determined to be 60 mm from the combustion

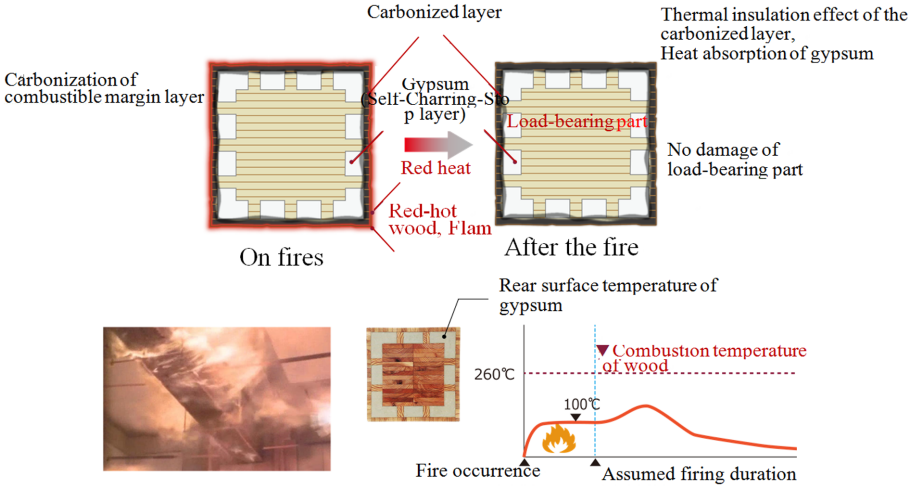
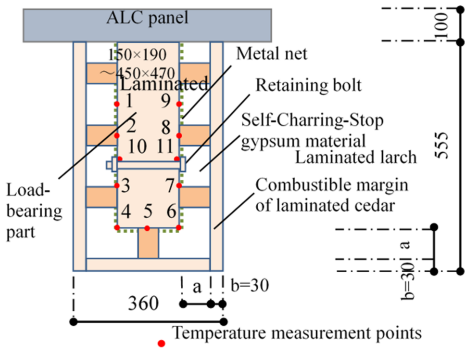


Figure 12. Mechanism to stop combustion of fire-resistant laminated timber.



Name	Notation	a(mm)	b(mm)	a+b(mm)
BM	BM55	55	30	85
	BM65	65		95
	BM75	75		105

a(mm):Depth of Self-Charring-Stop layer
b(mm): Depth of combustible margin layer

Figure 13. Diagram and parameter of test specimen of combustion test.

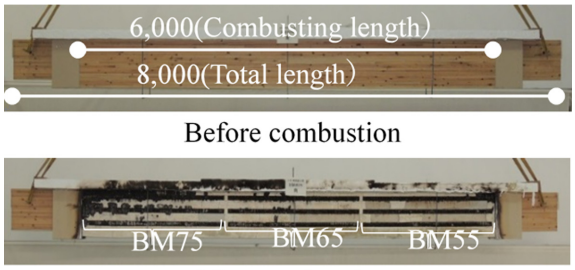


Figure 14. Test specimen before and after combustion.

test results of specimens with different thicknesses of 60 mm and 50 mm in one floor (Fig. 16).

In the fireproof test, the specifications of the fireproof coating on the floor surface were limited to the gypsum. In order to increase the variation of the composition of the floor, a top concrete was placed between the gypsum and the CLT panel to improve the vibration characteristics of the floor and to transmit the horizontal force, and in addition, a vibration-control material (8 sheets of foamed polyethylene or normal plywood) was placed between the top concrete and the CLT slab to improve the vibration characteristics, and their combustion tests were conducted to confirm the fireproof performance for two hours (Fig. 17).

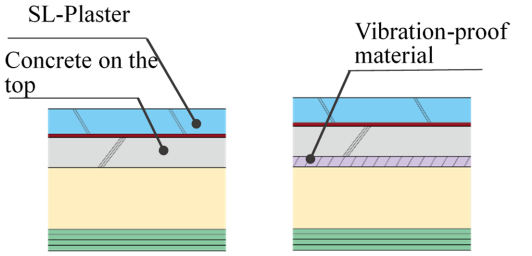
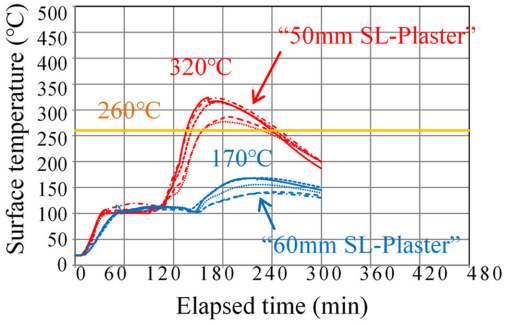


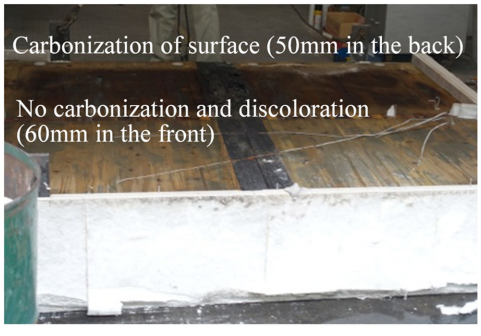
Figure 17. Options of 2-hour fire-resistant floor slab.

4.2.3. Development of fire-resistant laminated timber with reinforcement named "SAMURAI"

The size of the cross section of the laminated timber beam is decided by keeping the deflection quantity for the dead load within the allowable value. In recent years, it has become common for wooden buildings to have open spaces with few columns. Since the amount of deflection of the beam increases by the exponential of the span, the material volume of the laminated timber beam increases greatly and the construction cost rises in order to realize



Two-hour fire resistance test
Temperature transition of CLT surface
(Depth of "SL-Plaster": 50mm and 60mm)



After two-hour fire resistance test
CLT surface appearance
(Depth of "SL-Plaster": 50mm and 60mm)

Figure 16. Combustion test results of CLT slab.

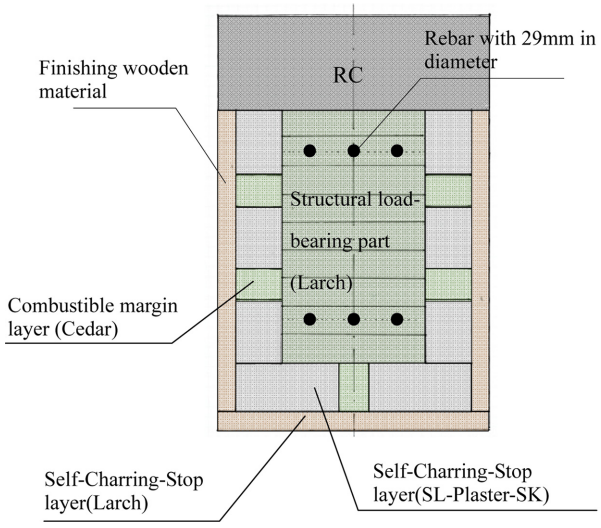


Figure 18. Cross-section diagram of fire-resistant laminated timber: "SAMURAI".

the open space with the large span. In view of the above background, in recent years, there has been an increasing need for a technology to realize a large span by minimizing the cross section of the beam as much as possible. To solve this problem, a large spanning approach was tried by inserting reinforcing bars inside the laminated timber.

Grooved laminas for inserting reinforcing bars are arranged on the upped and bottom layer of the "load-bearing part". After the reinforcing bars are inserted, the reinforcing bars and the laminas are integrated with an epoxy resin, and the laminas of the upper and bottom layer are bonded to form the laminated timber containing the reinforcing bars for the "load-bearing part". Fireproof layers consisting of "combustible margin layer" and "Self-Charring-Stop layer" are attached around the reinforced laminated timber to make a fire-resistant laminated timber with the "Self-Charring-Stop layer" named "SAMURAI" (Fig. 18).

The calculation of the beam stiffness is carried out by using the equivalent moment of inertia considering Young's modulus ratio of timber and reinforcement. The calculation is performed according to the equation (1) on the assumption that the Bernoulli-Euler theory is established. From the experimental results, it can be judged that the assumption of the Bernoulli-Euler theory is generally accepted up to the deflection angle (: R) of 15/1000.

$$I_e = \frac{b \cdot D^3}{12} + (n-1) \cdot (a_t + a_c) \cdot y_s^2 + (n-1) \cdot n_b \cdot \pi \cdot \frac{d_b^2}{64} \qquad (1)$$

Ie: equivalent moment of inertia of beam
b: beam width
D: beam depth
n: Young's modulus ratio of reinforcing bars to Young's modulus of timber
at: total cross-sectional area of tensile rebar
ac: total cross-sectional area of compressive rebar;
db: nominal diameter of rebar
ys: height of the rebar from the neutral axis of the beam
nb: total number of rebars in the beam

4.2.4. Development of reinforced concrete or steel frames with wooden earthquake-resistant walls

Under the Building Standards Law, fireproof performance is not required for earthquake-resistant walls that do not support long-term loads but only bear horizontal forces. It is very unlikely that an earthquake or typhoon and a fire will occur simultaneously. For this reason, there is a growing need for the use of wooden aseismic walls because they can be used while its surface being revealed without the fireproofing. The problems are to grasp the effect on the frame by installing the wooden earthquake-resistant wall in the frame of reinforced concrete or steel structure, to evaluate the rigidity and load-carrying capacity of the wooden earthquake-resistant wall, and to grasp the effect on the story-restoring force characteristics.

This paper describes the development of a reinforced

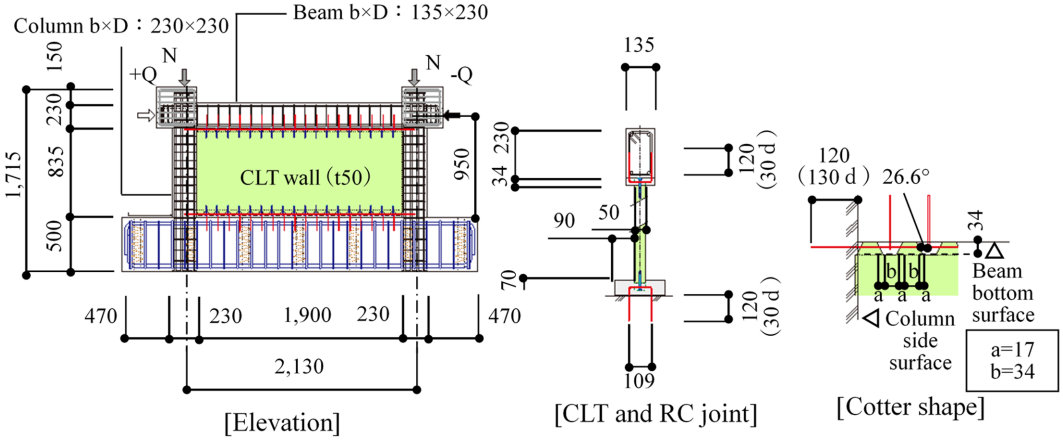


Figure 19. CLT test specimen without CLT wall joint for apartment house model.

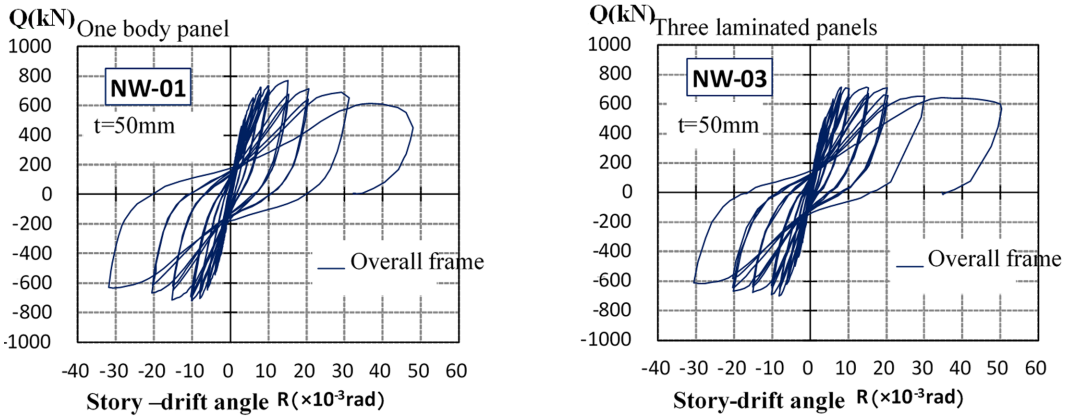


Figure 20. The relationships between shear force and story-drift angle of the test specimen.

concrete frame with CLT earthquake-resistant wall. The test specimens were constructed by installing the CLT earthquake-resistant wall in the column and beam frame assuming the floor-height and span of apartment houses and schools, and 6 specimens were prepared with the thickness of the CLT and the presence or absence of the panel-to-panel joint as parameters (Fig. 19). The joining of the CLT wall and the RC frame will be described. The upper and lower ends of the CLT wall are provided with a ruggedness cotter, which is embedded in the RC beam to be joined. A cotter was not provided on the left and right sides of the CLT wall, and about 20 mm of the wall was embedded in the column. (Fig. 19).

The relationships between shear force and story-drift angle of the test specimen obtained in the experiment are shown (Fig. 20). Both specimens are designed to have the beam-yielding preceded, and in the experiments, the bending yielding of the beam occurred as expected, and the relationship between the total shear force and the story-drift angle showed good deformation performance without a rapid decrease in strength until deformation exceeding 30/1,000 rad even after the maximum strength was exerted. In addition, no damage such as shear-failure of the CLT panel itself was observed until the end of the test (Fig. 20). As a result of making a skeleton curve and separating the shear force of the whole frame into the shear force shared by the CLT earthquake-resistant wall and the column, it was confirmed that the CLT aseismic wall can bear up to about 70% of the shear force of the whole frame. From the experimental results, the initial stiffness of the CLT earthquake-resistant wall is set as the sum of the initial stiffness of the peripheral frame and the initial stiffness of the CLT panel obtained by the following equation.

5. Application of 2-hour Fire-resistant Laminated Timber to Mid-rise Buildings

Buildings made of 2-hour fire-resistant laminated timber with the “Self-Charring-Stop layer” have been



Figure 21. PARKWOOD TAKAMORI; Outside view.

constructed since 2018. In this section, two typical buildings are introduced.

5.1 Parkwood Takamori

5.1.1 Building outline

- Design and supervision: Takenaka Corporation
- Building site: Sendai, Miyagi
- Building function: residential
- Total floor area: 3,486.6 m^2
- Building height: 33.7 m
- Building scale: 10 floors above ground
- Structure: Earthquake-resistant, wooden and steel structure

5.1.2. Outline of Structural Design

The outline of the structural framework of this building is shown in Figs. 22. The main framework is composed of steel frames, CLT floor slabs are installed as a wooden structural member on a part of the 4th to 10th floors, CLT

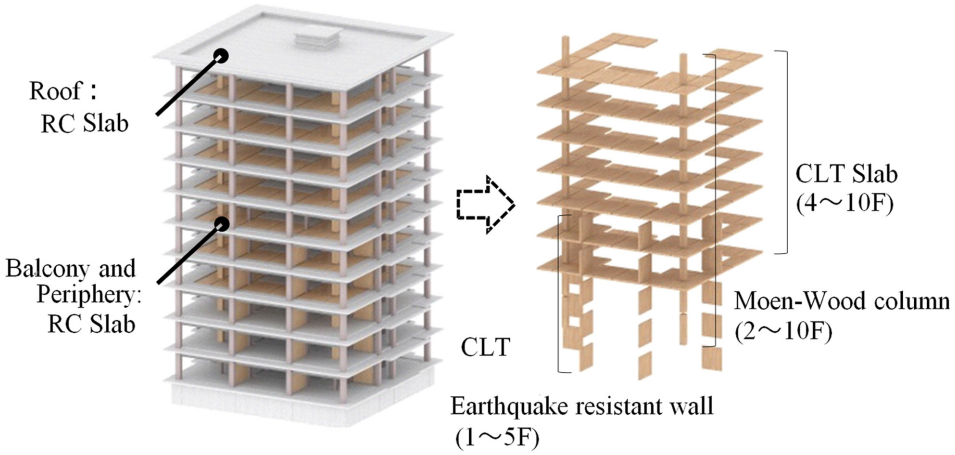


Figure 22. Illustration of skeleton and wooden member arrangement.

earthquake-resistant walls are installed on the 1st to 5th floors, and fire-resistant laminated timber columns with the "Self-Charring-Stop layer" named Moen-Wood (patented) are installed on the 2nd to 10th floors as long-term axial support columns. The upper four stories, that is, the columns on the 7th to 10th floors, are fireproof for one hour, and the columns on the 2nd to 6th floors are fireproof for two hours. Since this building is an apartment house, it is necessary to improve the sound insulation performance of the CLT floor. Therefore, concrete with a thickness of 80 mm is placed on the top of the CLT. A connector is installed in the upper part of the CLT to integrate the CLT with the reinforced concrete.

The upper frame is a rigid frame structure with three spans in both the X and Y directions. The seismic force is assumed to be 100% by the steel frame, and the CLT walls are arranged as additional earthquake-resistant elements. Since this building weight is 0.85 t/m^2, lighter than the ordinary reinforced concrete apartment house, the foundation is possible to be designed as the spread foundation (: raft foundation with soil improvement) instead of the pile foundation.

5.2. Flats Woods Kiba

5.2.1. Building outline

- Design and supervision: Takenaka Corporation
- Building site: Tokyo
- Building function: residential
- Total floor area: 9,150.7 m^2
- Building height: 40.8 m
- Building scale: 12 floors above ground
- Structure: Earthquake-resistant, reinforced concrete, steel and wooden structure

5.2.2. Outline of structural design

FLATS WOODS KIBA is a 12-story apartment house for single persons provided by company. There are common facilities such as cafeteria, gym, and private study room on the 12th floor, and there are a total of 252 dwelling units from the 1st floor to the 11th floor. The floor has approximately 26 m in the width and 34 m in the depth, the height of the building is 40.8 m, and the floor height of the typical floor is 2.95 m. The wooden members are arranged in corner rooms on the standard floor and rooms in the common area on the 12th floor.

Fig. 25, 26 and 27 shows typical floor plan, sectional framing plan and illustration of structural skeleton,

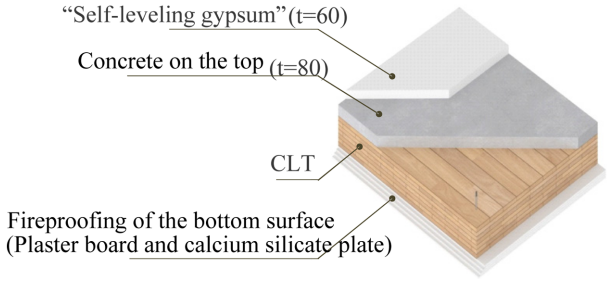


Figure 23. Configuration of CLT floor.



Figure 24. FLATS WOODS KIBA; Outside view.

respectively. This building has a hybrid structure of reinforced concrete and wood, and is partially steel-framed. As earthquake-resistant elements, reinforced concrete aseismic walls are arranged in a parallel cross shape in the standard floor. The performance as continuous-layered aseismic walls is improved by fastening the shear walls with mega beams installed on the 12th floor. In addition, higher seismic performance is ensured by installing seismic-isolation devices at the bottom of the buildings.

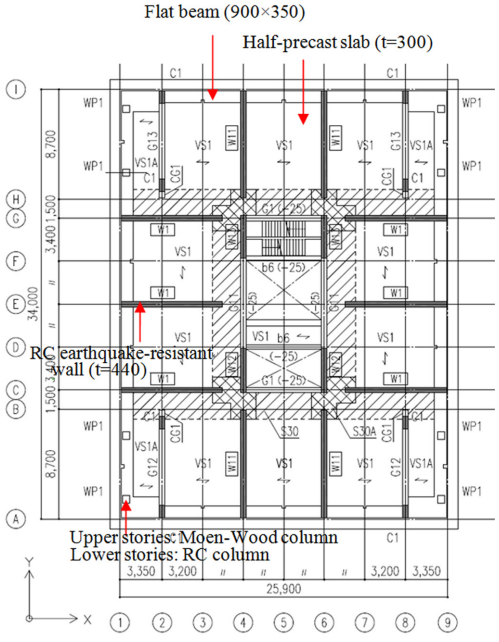


Figure 25. Typical floor plan.

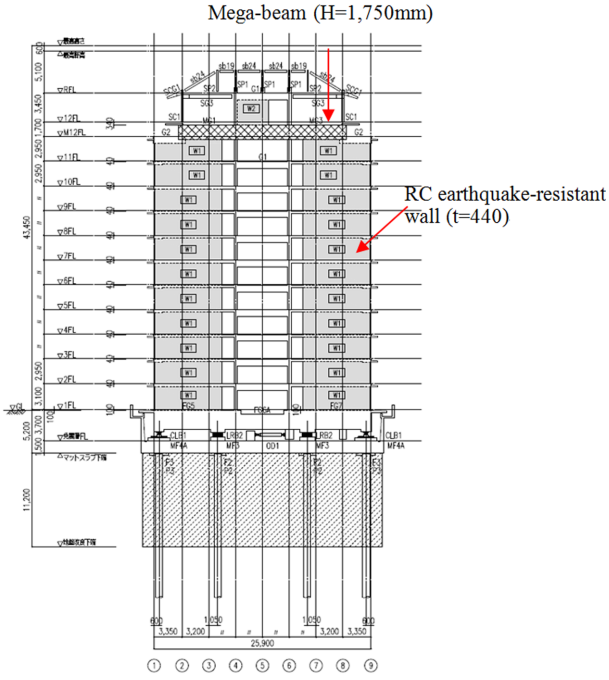


Figure 26. Sectional framing plan.

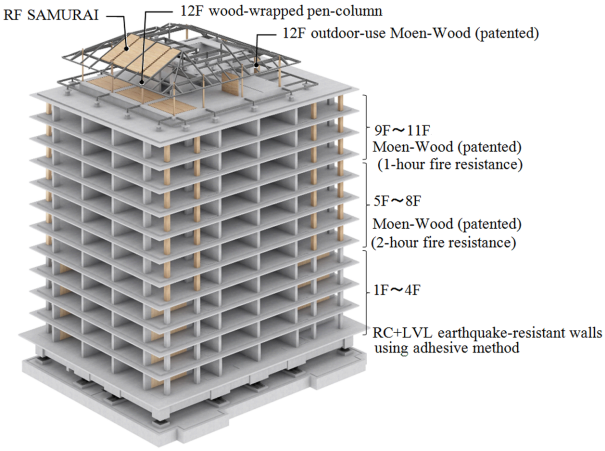


Figure 27. Illustration of skeleton and wooden member arrangement.

Various new structural and construction methods, including experimental ones, have been adopted for the wooden components of this building. (Figs. 27) On the 12th floor, a fire-resistant laminated timber beam with the "Self-Charring-Stop layer" named "SAMURAI" and the "Wood-wrapped pen-column" which is a very slender reinforced concrete column with a fireproof covering of LVL are adopted for the first time. In addition, fire-resistant laminated timber columns with the "Self-Charring-Stop layer" named Moen-Wood (patented) for 1-hour fire resistance, 2-hour fire resistance, were installed from the 9th floor to the 12th floor, from the 5th floor to the 8th floor, respectively, and earthquake-resistant RC walls with LVL panels glued to those surfaces were installed from the 1st floor to the 4th floor. (Fig. 27)

6. Challenges to High-rise Wooden Building

6.1. Further Technological Development Issues

The revision of the Building Standard Law and the development of fire-resistant laminated timber have made it possible to construct mid- to high-rise wooden buildings in Japan. In order to realize the spread of mid- to high-rise wooden structures and the further higher wooden buildings in the future, the following technological development is considered necessary.

6.1.1. Development of Structural Technologies

With the increase in the building height, an unprecedented amount of axial force will be applied to the columns. Current technology requires very large cross-sectional columns to support this axial force, which severely conflicts with the architectural planning. In order to reduce the cross section of the column, it is necessary to develop a column capable of high axial force using higher strength materials than before or a hybrid column with materials other than wooden materials.

As the building becomes higher, the weight of the

building increases, so the seismic force in the lower stories in the building also increases. In the current design method, all of the seismic force is imposed on the reinforced concrete structure or the steel structure, but in order to promote the development of high-rise buildings, it is considered that a certain amount of seismic force should be borne by the wooden structure in view of the economic efficiency as well. Therefore, it is necessary to develop a mechanism to absorb energy at the beam-column joint of fire-resistant laminated timber.

At present, the fire-resistant laminated timber with the "Self-Charring-Stop layer" have the fireproof up to 2 hours, but the implementation of the technology with the fire-resistant performance for 3 hours is indispensable in order to make the building over 14 stories into the wooden structure.

6.1.2. Development to Realize Attractive Space as Architecture

Low- to mid-rise buildings using fire-resistant laminated timber have been created until now, but there are some restrictions on the use of fire-resistant laminated timber, which may not meet architectural requirements. For example, when fire-resistant laminated timber and claddings, fire-resistant partition walls, and fire shutters are in contact with each other, a gap is formed in the joint part due to combustion of the "combustible margin layer", and it becomes impossible to prevent the penetration of flames and smoke. The building plan is designed so that the claddings, fireproof partition walls, fire shutters, and fire-resistant laminated timber do not directly meet each other, since the original role of the building cannot be fulfilled. In the future, it is necessary to develop a joining method with various building equipment, fittings, and claddings which can maintain fire resistance.

In the beams of reinforced concrete and steel structure, through-holes are provided to penetrate the facility piping, and reinforcing techniques exists to reinforce the cross-sectional defect, but the reinforcement technology has not been established in the fire-resistant laminated timber. For this reason, the piping runs under the beam, and the ceiling is lowered or the piping is exposed, so that there are many cases where does not become a rich space as an architectural space. In the future, it is considered essential to develop a reinforcement method for through-holes of fire-resisting laminated timber beam.

6.2. Project Concept; ALTA LIGNA TOWER

6.2.1. Architectural Concept

It is a high-rise wooden complex building planned in 2017 as a concept model to promote wooden and woody buildings in the redevelopment of central urban areas in Japan. An architectural model with higher feasibility is aimed at by setting the completion target to 2025. In this building, the selection of the most suitable material and structure to put in the specific place without sacrificing the function originally required for the building by the wooden usage was the basis of the plan.

Although it is a concept model in an imaginary site, the volume of the building was set in consideration of the urban planning method so that it can be applied in a common site. As a result of the volume-study, this model was set as a building with a 20-floor office and commercial facilities. 14 stories from the 7th floor to the 20th floor have increased flexibility as offices using wooden members with 1-hour or 2-hour fire resistance. The lower stories below 6th floor were made to be a framework suitable for commercial use as a hybrid structure with steel frame. It not only fulfills the functions of architecture, but also firmly maintains in the overall design that the "Structural design" which is the beauty of Japanese traditional wooden architecture, is exposed to the outside by making the joint of columns and beams into a wooden frame-work.

6.2.2. Structural concept

This building has a hybrid structure consisting of steel structure in the core which bears the horizontal force and wooden structure arranged in the living room space.

In the frame covering the office space of the building, the wooden-framed joint of column and beam is used. This timber-framed joint has the "Coupled-Beam System" with beams attached to both sides of the column. Since a



Figure 28. ALTA LIGNA TOWER; Outside view.



Figure 29. ALTA LIGNA TOWER; Inside view.

large space without columns is required in the office space according to the architectural plan, the beams on the office space are often long span beams. The size of the cross section of a long span beam is commonly determined by the amount of deflection under long-term load. In this model, by making this long span beam as a coupled-beam, the floor area borne by one beam can be reduced, and the size of the cross section of the beam can be suppressed by the increase of the bending-rigidity of the beam end due to the close contact of the column and beam, and a rich column-free space can be realized within the limited floor height.

In the peripheral frame of the building, the joint of column and beam is made to be a rigid joint. In addition, the CLT shear wall should be placed in a position where there is no hindrance in the building plan to bear the horizontal force. Thus, the horizontal force borne by the steel frame can be reduced, and the uplift of the foundation transmitted by the steel frame can be reduced, and the construction cost can be reduced.

With the increase of building height, the columns have to bear a large axial force that has never been experienced before. In order to ensure that this high axial force is transmitted to the lower stories, a higher strength wooden material should be developed and adopted for the columns.

The floor slab is a composite slab consisting of a CLT and a reinforced concrete in order to satisfy structural performance as a horizontal diaphragm, sound insulation and blocking performance as a boundary floor, and to create a rich woody space. Even if the CLT burns out in a fire, the floor weight should be supported by the reinforced concrete floor itself, and the CLT floor should be used uncovered without fireproof coating.

7. Conclusion

Due to concern over global environmental issues, the active introduction of wood-based architecture has become a global trend.

Even though there are difficult conditions peculiar to Japan that high-rise buildings must be fireproof, which are not seen in other countries, but it is expected that wooden buildings will be required to be much higher. The technology development necessary for this requirement will be advanced, and in the near future, it is expected to be possible to build super high-rise buildings with wooden structures as well as reinforced concrete and steel-framed structures.

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