Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Study on a Development of Wooden Parallel Chord Truss Structure with Lumber in Mori-machi, Hokkaido

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Abstract

In this study, we developed a parallel chord truss construction method. It uses three types of lumber in Mori-machi for each member in the right places and can be processed on standard lines of residential pre-cut processing machines. This method is easy to assemble using dovetail, drift pin, and screw joints, and sandwiching the chords by bundles. This paper includes the joint tests, the full-scale tests, and the creep tests, and we conducted them to verify the constructability of this method and to obtain basic data on structural performance for practical use. We obtained results as follows; (1) The simplicity of the construction method was verified through the fabrication of the specimens of these tests. (2) The mechanical properties of different wood species, the number of screws, and specimen shapes were confirmed in the joint tests. (3) the full-scale tests were conducted on the 4.4 m and 11 m spans, and several differences in mechanical properties were observed between the different tree species and spans. the deformation increase coefficient to slip at the joints was confirmed. (4) the creep tests were conducted with the 6.6 m span specimen, and the deformation increase coefficient to creep deformation was confirmed.

Keywords: parallel chord truss, dimension lumber, glued laminated timber, assembled three lumbers of different species, joints using both drift pin and screw

1. Introduction

In Mori-machi, Kayabe-gun, Hokkaido, Japan, the three types of wood "Japanese red cedar, Todo fir, and Japanese larch" are planted in the same area, and many of the trees are reaching their harvesting stage. On the other hand, many existing public buildings in Mori-machi progress 50 years old, and these aging buildings need reconstruction. Based on the above, we developed the parallel chord truss construction method that can be constructed locally and realize long spans by utilizing these resources.

Figure 1 shows the overall picture and the overview of the parallel chord truss construction method. This method uses commonly available timber that can be processed on standard lines of residential pre-cut processing machines. This system is easy to assemble by sandwiching the chords by bundles. In addition, to take advantage of natural resources in the area, we consider the use of three species of trees grown in Mori-machi for each member in the right places.

To verify the constructability of this construction method and to obtain basic data on structural performance for practical use, we conducted the joint tests, the full-scale tests, and the creep tests, and a trial design using these results.

Figure 1: Overall picture (left) and overview of the parallel chord truss construction method (right)

2. Characteristics of parallel chord truss

Figure 2 shows the components of the parallel chord truss construction method. Chapter 2 explains the characteristics of this construction method.

The chords were made of glued laminated timber composed of heterogeneous grade lumber. For the parallel chord trusses that exceed the maximum length of the manufactured members (6000 mm), the upper chords are joined by a dovetail joint, and the lower chords are joined by drift pinned joint with steel insert plate to realize long spans. the diagonal-chord joints were notched 40 mm deep to transmit diagonal compression stress to the vertical and horizontal components. The depth of 40 mm was determined based on the maximum dimension that could be machined on a standard line of residential pre-cut processing machines. The diagonals were made of glued laminated timber composed of homogeneous grade lumber or lumber of the same width as the chords, and the ends of the diagonals were machined to fit into the 40 mm notches in the chords described above. The bundles were made of dimension lumber (nominal size: 2×6), and the chords were sandwiched by the bundle from both sides. The bundle-chord joint was jointed by drift pins and screws. It simplifies the positioning of wood during construction and prevents the bundles and diagonals from coming off the chords. First, two drift pins are driven in to set the position, and then screws are driven to pull the bundles and chords together. The screw heads are aligned with the face of the bundles, and the screws are staggered from both sides to ensure even tension. This joint serves to restrain the diagonals out of the truss plane during construction. The truss of 11 m span was completed in about two hours by four adults who have no experience in construction, and we suggested the simplicity of this construction method.

Furthermore, to take advantage of the natural resources, we considered the use of three species of trees grown in Mori-machi for each member in the right places. In this study, as an example, Japanese larch with high bending performance was used for the chords, Todo fir, which is white and has high design characteristics, was used for the bundles, and Japanese red cedar with low distortion was used for the diagonals. The distribution of Japanese red cedar, Japanese larch, and Todo fir around Mori-machi and their material properties are reported in Refs [1] and [2].

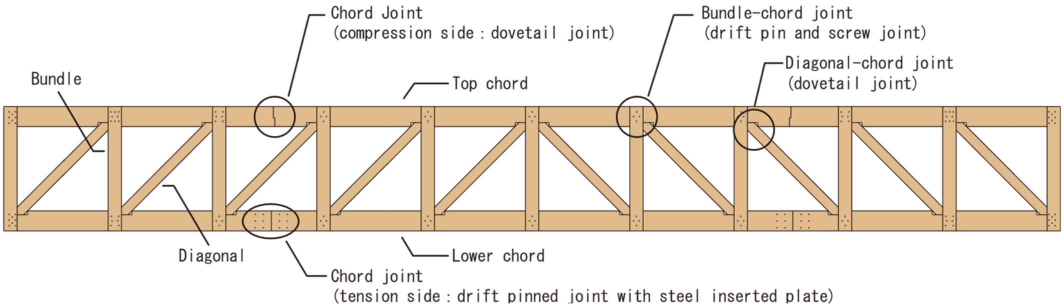

Figure 2: Components of the parallel chord truss construction method

3. Joint test

The joints between the bundles and the chords consist of drift pins and screws. In Japanese standards, the edge distance of the screws is based on the same Japanese standard as that of the drift pins to minimize the beam depth of the chords, and some of the specifications are lower than the standard. Therefore, in Chapter 3, the joint tests were conducted on the bundle-chord joints to verify the structural performance of the specifications of this construction method.

3.1. Test overview

Figure 3 shows the method of joint test and joint specifications. The test specimen was a model of a bundle-chord joint of the method, with two types of nodes: one located in the middle of the chords (hereafter referred to as "middle type") and the other at the end of the chords (hereafter referred to as "end type"). The components of the specimens were dimension lumber (nominal size: 2×6) for the bundles (Actual size: 38 mm thick, 140 mm wide, and made of a knotless portion of No.2 grade of Japanese Agricultural Standard (JAS)) and glued laminated timber for the chords (105 mm thick, 210 mm wide, glued laminated timber composed of heterogeneous grade lumbers). Drift pins (SGD400 of Japanese Industrial Standards (JIS), φ12×181 mm) and screws (Sinegic Panelead S equivalent, screw diameter of 8 mm, total length of 170 mm, threaded length of 70 mm) were used as joints. The position of the drift pins was set by the standard for Structural design of timber structures [3]. The same criteria for the location of the screws as for the drift pins were used as shown in figure 3. Note that the edge distance of some of the end type screws is less than the standard. The joint specifications are based on two drift pins and the number of screws is variable. The middle type has four types of specifications: zero (P2V0), two (P2V2), four (P2V4), and six (P2V6) screws. Three types of specifications were used for the end type, excluding P2V2. The middle type consisted of four species: Japanese red cedar, Todo fir, and Japanese larch, and a mix of Japanese larch for chords and Todo fir for bundles (hereinafter referred to as "mixed specification"), while the end type consisted of one species, Todo fir. The load was applied repeatedly in one direction, and the load and the relative displacement between each bundle and the bottom of the chords were measured. The number of specimens for the middle type was three, and the number of specimens for the end type was six.

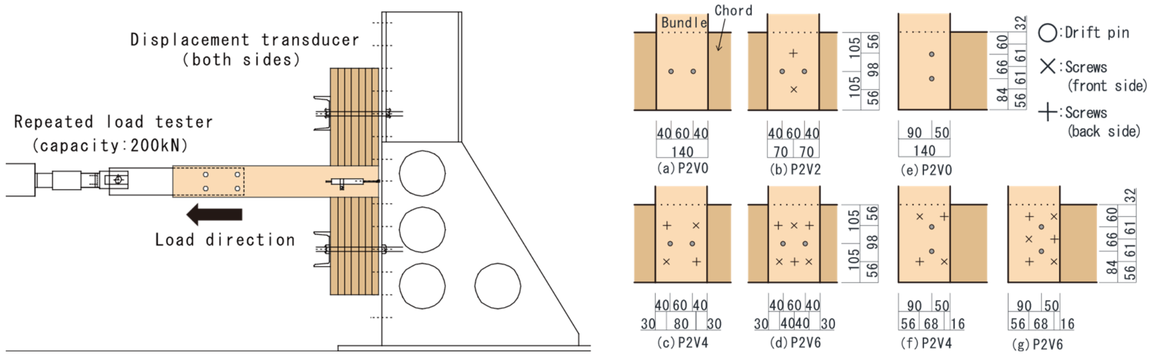

Figure 3: Method of joint test (left) and joint specifications (right)

3.2. Results and discussion

Figure 4 shows the typical condition of the specimens after the test and the enveloped load displacement relationship curve. For the middle type, Japanese larch had the highest yield strength ultimate strength and initial stiffness, while Todo fir and Japanese red cedar were about 70% to 80% of those of Japanese larch, and the mixed specification was intermediate between Japanese larch and Todo fir. On the other hand, Japanese larch had the lowest ultimate displacement, while Todo fir and Japanese red cedar had higher deformation performance. For the end types (Todo fir only), the yield and ultimate strength of the end types were only 80 to 90% of those of the middle types, while the ultimate displacement of the end types was significantly lower than that of the middle types. This is because the end type had a less tough fracture mode of cracking of the chords.

As for the relationship between the number of screws and each joint performance, the average values of yield strength, ultimate strength and initial stiffness increased in proportion to the number of screws, regardless of the species, while the ultimate displacement decreased. the load was reduced due to cracking from the screws. Especially in the case of P2V4 in the middle section type, cracks that started at the screwing-in position reached the pre-drilling hole for drift pin and formed a large crack, resulting in a large drop in load, which was a factor in the large variation. On the other hand, in the case of P2V2 or P2V6, even if a crack occurred from the central screw position, the drift pin suppressed the expansion of the crack, and stable performance was obtained. This suggests that joint performance, especially toughness, improved by adjusting the arrangement of the joints.

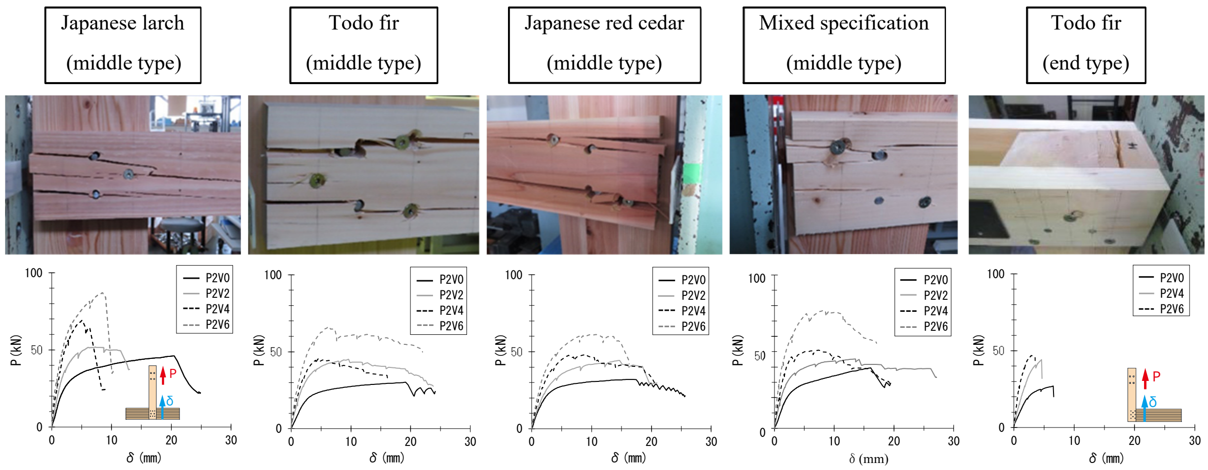

Figure 4: Typical condition of the specimens after the test (top) and the enveloped load displacement relationship curve (lower)

4. Full-scale test

In Chapter 4, the full-scale tests were conducted to obtain basic data for understanding the differences in the mechanical properties of this construction method depending on tree species and spans. In order to confirm the effects of tree species, the tests were conducted on three types of specimens: "LT" with Todo fir for each member, "LK" with Japanese larch for each member, and "LM" with Japanese red cedar for the diagonals, Todo fir for the bundles, and Japanese larch for the chords. In each type, the specimens had 11 m spans. In addition, to understand the effect of different spans, the tests were conducted on specimen "ST", which had 4.4 m span without changing the truss depth, and the pitch of bundle and diagonal, and each member was made of Todo fir. For the classification of spans, LK, LT, and LM are collectively referred to as "L series" and ST as "S series".

4.1. Test overview

Figure 5 shows the overview of the specimen and the method of full-scale test. The load was a symmetrical four-point load with a distance of 2.2 m between load points. The components of the specimens were dimension lumber (nominal size: 2×6, Actual size: 38 mm thick, 140 mm wide, No.2 grade of Japanese Agricultural Standard (JAS)) for the bundles, glued laminated timber (105 mm thick, 210 mm wide, glued laminated timber composed of heterogeneous grade lumbers) for the chords, and glued laminated timber (ST, LT and LK) and lumber (LM): (105 mm thick, 105 mm wide, glued laminated timber composed of homogeneous grade lumbers or lumber) for the diagonals. Drift pins were made of SGD400 of Japanese Industrial Standards (JIS) (φ12×181 mm), and screws were made of Sinegic Panelead S equivalent (screw diameter of 8 mm, total length of 170 mm, threaded length of 70 mm). The steel plate used for the L series drift pinned joint with steel insert plate was SS400 (9 mm thick and 210 mm wide), and the drift pins were polished round steel SGD400 (φ12 × 105 mm). The specifications for the bundle-chord joint were the same as in Chapter 3 joint test, and the specifications for the other joints were as shown in Figure 5. A total of four specimens were fabricated, one for each type.

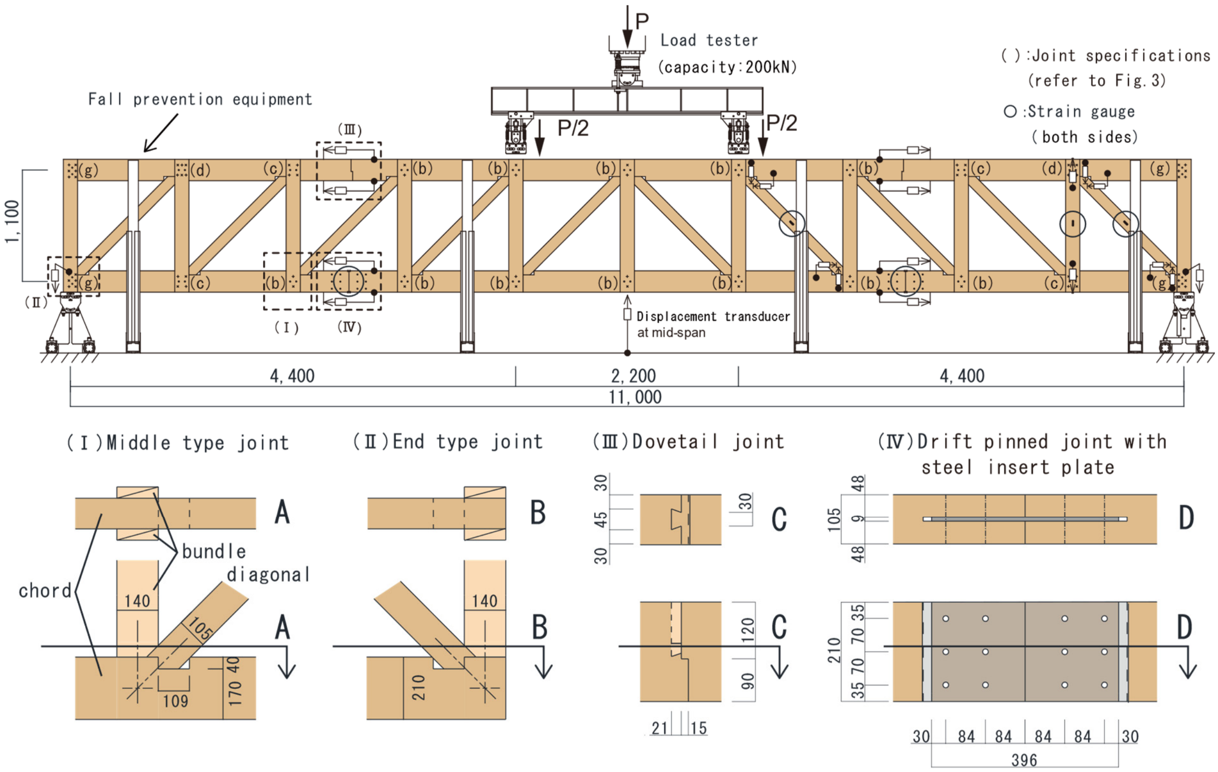

Figure 5: Overview of the specimen and the method of full-scale test (A ~ D: joint cross section)

4.2. Results and discussion

Figure 6 shows the load mid-span deflection relationship curve, and condition of the specimens after the test. The maximum load was in the order of ST > LK > LM > LT. The final failure shape in this method was determined by one of three types of joints: the drift pinned joint with steel insert plate installed in the lower chords, the bundle-chord joint, and the lower chord end. In this result, it was confirmed that the structural performance of the diagonal-chord joint at the lower chord end was dominant for short spans, while the structural performance of the drift pinned joint with steel insert plate and the bundle-chord joint was dominant for long spans.

The initial stiffness obtained from the test is compared with the analytical values. the elastic analysis model assumes that the members are wires, and the fulcrums are pins and rollers. The elastic analysis model showed that the stiffness of the L series was 2.13 to 1.89 times greater than the tested values, and the S series was 2.64 times greater than the tested values. In this result, the actual deflection in this method can be estimated by assuming that the deformation increase coefficient due to joint slip for the elastic deflection in the elastic analysis results is 2.2 for the L series and 2.7 for the S series.

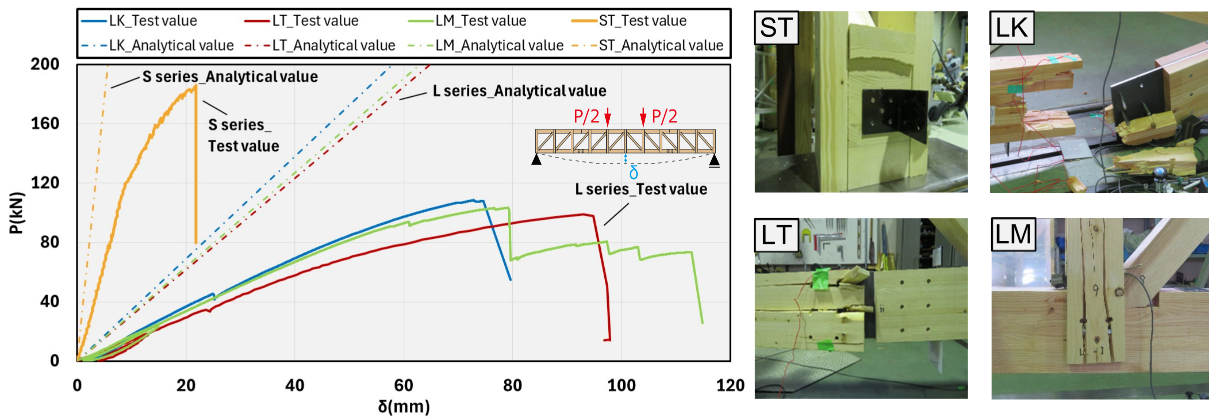

Figure 6: Load mid-span deflection relationship curve (left) and condition of the specimens after the test (right)

5. Creep test

In Chapter 5, the creep tests were conducted to determine the long term performance of this construction method.

5.1. Test specimen

Figure 7 shows the creep test scene. The components of the test specimen were the same as the full-scale tests in Chapter 4. Due to environmental restrictions, the test specimens had 6.6 m span without changing the truss depth, and the pitch of bundle and diagonal, and two specimens were installed in parallel together.

The test specimen was created in a box shape by placing two trusses 1000 mm apart, passing horizontal structural members through the tops of the bundles except at the ends and load points, and applying plywood to the truss ends.

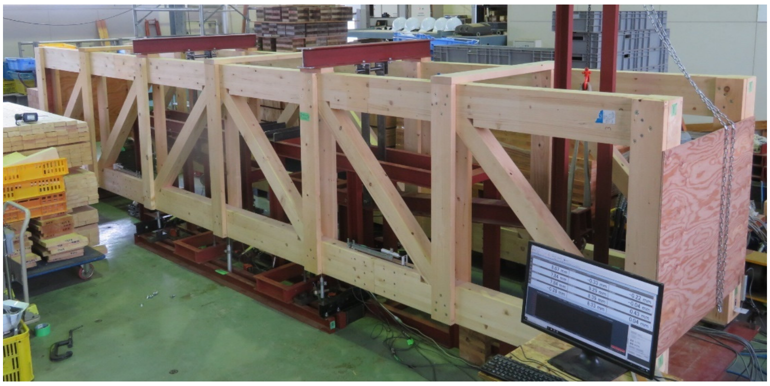

Figure 7: Creep test scene

5.2. Test method

Figure 8 shows method of creep test. The creep tests were conducted with a span of 6.6 m (span to truss depth ratio of 6). The force applied was a two-point load with three equal parts. The load was 31.53 kN per truss. This load was applied to the dead load of 1350 N/m^2, the snow load of 1800 N/m^2, the pitch of 0.91 m, and a span of 11 m, assuming the target area of Mori-machi, Kayabe-gun, Hokkaido, Japan. The load was applied by suspending a predetermined number of steel plates on a moment arm. When the ultimate load of the test specimen was defined as the ultimate load of the joint, it was determined by the shear failure of the diagonal-chord joint at the lower chord end, and the load was 84 kN. The applied load was equivalent to 38% of the ultimate load. The deflection was measured at mid-span using a displacement transducer of 100 mm capacity (DTH-A-100, Kyowa Dengyo Co., Ltd.), which was set at the bottom of the specimen. The deflection was measured every minute after loading.

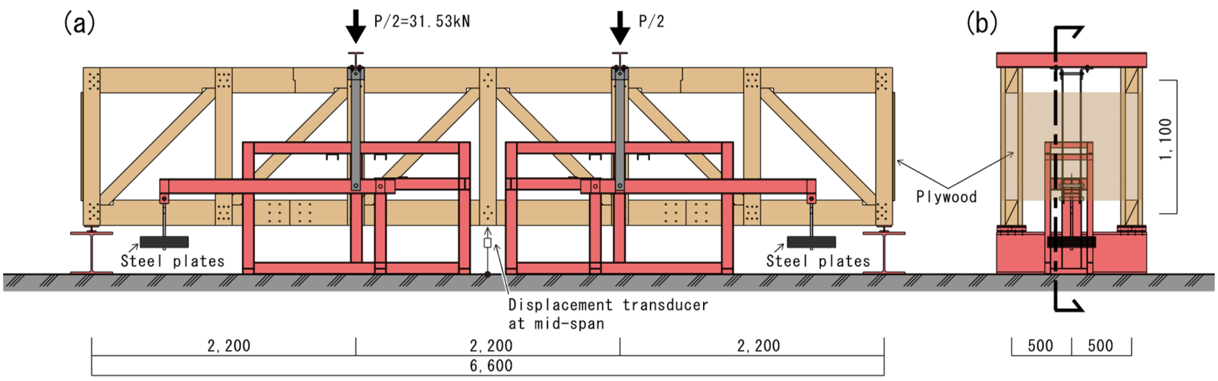

Figure 8: Method of creep test ((a): cross section, (b): side view)

Figure 9 shows the ambient air condition. The tests were conducted at the laboratory of Hokkaido Forest Products Research Institute. Although the humidity in the laboratory was uncontrolled, the temperature in winter was warmed by air heaters. During the test, the maximum temperature was 13.3°C, the minimum was 2.6°C, and the average was 8.8°C; the maximum humidity was 65.2%, the minimum was 23.1%, and the average was 36.2%. The tests began on 26th of January, 2024, and was ongoing as of 15th of April, 2024. In the case of uncontrolled temperature and humidity, it is desirable to consider at least one year of observed data to account for the effects of mechanosorptive deformation due to seasonal changes, but this paper considers 59 days of data conducted through 25th of March, 2024. Note that measurements were not taken from 9th to 10th of March due to a simultaneous power outage.

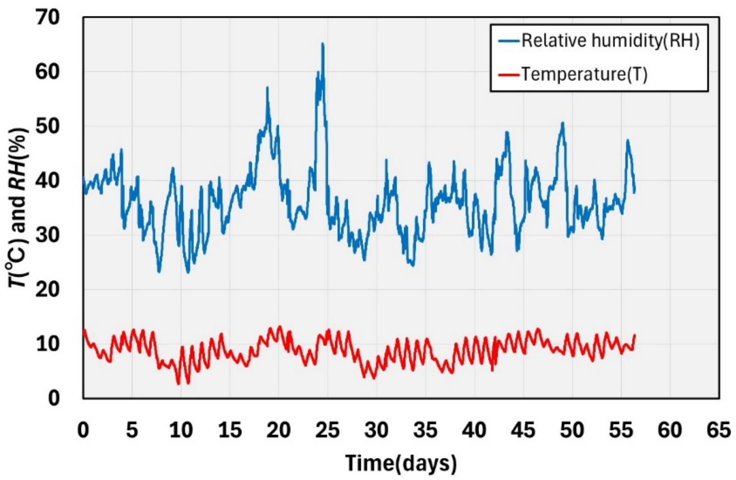

Figure 9: Ambient air condition

5.3. Results and discussion

In this study, the creep deflections of the specimens were estimated by two methods to predict a creep deflection after 50 years of load duration. One prediction method by power law is made by the following equation:

$$\delta_{m(t)} = \delta_0 + \delta_{C(t)} = \delta_0 + At^N \tag{1}$$

where,

$\delta_{m(t)}$ = deflection at mid-span after t minutes from the start of loading (mm), δ_0= initial deflection at the moment of loading (mm), $\delta_{C(t)}$= increment of creep deflection after t minutes from the start of loading (mm), t = elapsed time (min), A and N = creep constants.

Another prediction method based on creep adjustment factor [4] is made by the following equation:

$$K_{b(t)} = \delta_0/\delta_{m(t)} = 10^e t^f \tag{2}$$

where,

$K_{b(t)}$= creep adjustment factor, e and f= creep constants.

As in previous studies, the estimated values for both equations were obtained using two methods: the method using all observed data and the method excluding data for less than 24 hours after loading [5]. Although the maximum value of deflection at mid-span $\delta_{m(t)}$ of each specimen was about 0.6 mm different, the average value of the two specimens was used to obtain the estimated relative creep values in this paper. In addition, we did not take into account the wood embedment at the fulcrum in obtaining the estimated values.

Figure 10 shows the correlation between $\log_{10} t$ and $\log_{10} \delta_{C(t)}$ by Eq. (1) or $\log_{10} \delta_0/\delta_{m(t)}$ by Eq. (2), and the regression line. Regardless of the difference in the equation, the regression line excluding data for less than 24 hours was more consistent with the observed data than the regression line for all observed data.

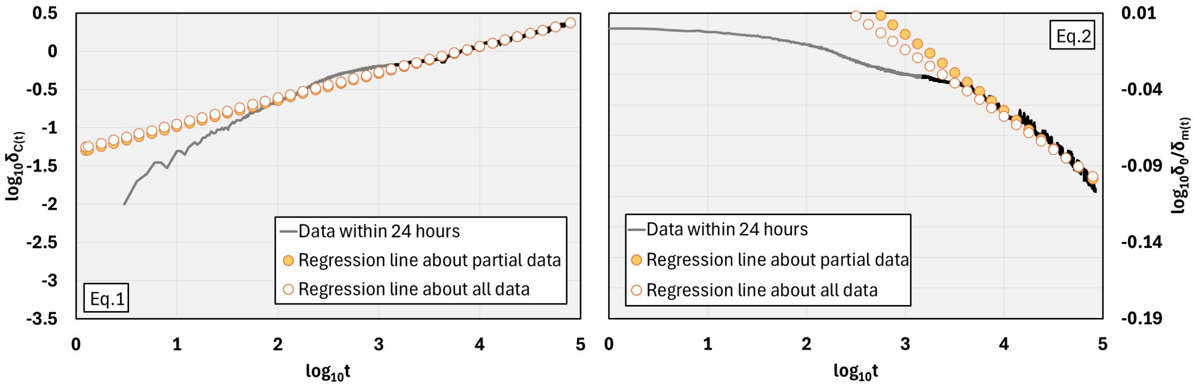

Figure 10: Correlation between $\log_{10} t$ and $\log_{10}\delta_{C(t)}$ by Eq. (1) or $\log_{10} \delta_0/\delta_{m(t)}$ by Eq. (2) and regression line

Figure 11 shows the relative creep (δ_m/δ_0) of observed data and estimated values by Eq. (1) and by Eq. (2). Looking at the differences in the equations, the estimated values by Eq. (1) were larger up to 3 days, then reversed, and the estimated values by Eq. (1) tended to be larger after 35 days. In terms of estimated values for all observed data, the estimated values by Eq. (1) was in better coincide with the observed data than Eq. (2). In terms of estimated values for the excluding data for less than 24 hours were examined, as with the estimated values for all observed data, the estimated values by Eq. (1) was in better coincide with the observed data than Eq. (2).

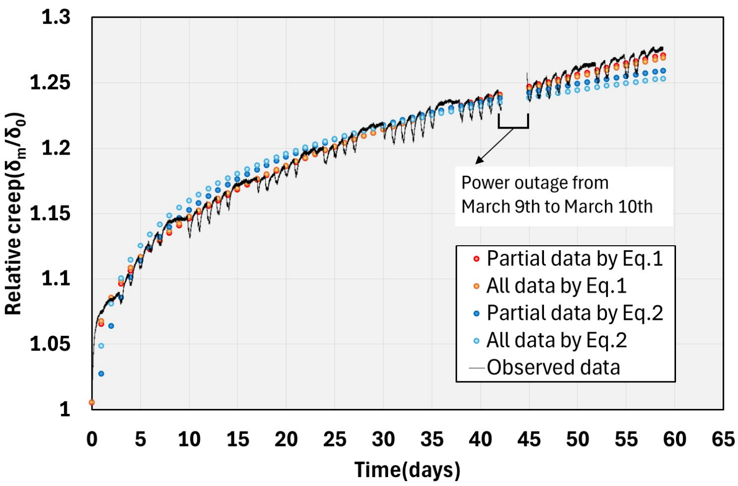

Figure 11: Relative creep (δ_m/δ_0) of observed data and estimated values by Eq. (1) and by Eq. (2)

Table 1 shows the coefficient of determination, creep constants and the relative creep after 59 days (δ_{59d}/δ_0) or 50 years (δ_{50y}/δ_0) load duration estimated by Eq. (1) and by Eq. (2). The creep constants by Eq. (1) for air-dried lumber and glued laminated timber are all about 0.2 [6], but compared to these, the constants in this tests were significantly smaller for A/δ_0 and larger for N, regardless of the equation or the estimated values of data for less than 24 hours.

The relative creep at 59 days (δ_{59d}/δ_0) was 1.28~1.26 with little difference due to the different equations. On the other hand, the relative creep after 50 years (δ_{50y}/δ_0) showed 3.00~2.88 by Eq. (1) and 1.68~1.62 by Eq. (2), showing a remarkable difference.

Table 1: Coefficient of determination, creep constants and relative creep after 59 days (δ_{59d}/δ_0) or 50 years (δ_{50y}/δ_0) load duration estimated by Eq. (1) and by Eq. (2)

	Eq.1						Eq.2					
Data	R^2	A/δ_0	N	δ_0	δ_{59d}/δ_0	δ_{50y}/δ_0	R^2	e	f	δ_0	δ_{59d}/δ_0	δ_{50y}/δ_0
Partial	0.99	0.066	0.35	8.96	1.28	3.00	0.96	-0.012	-0.050	8.96	1.26	1.68
ALL	0.98	0.068	0.34		1.27	2.88	0.92	-0.021	-0.044		1.26	1.62

These results indicate that the method that excluding data for less than 24 hours has a higher compliance rate for the estimated values, and the estimated values by Eq. (1) has a higher compliance rate for the relative creep by deflection at mid-span $\delta_{m(t)}$. The largest relative creep after 50 years (δ_{50y}/δ_0) was 3.00 by Eq. (1), excluding data for less than 24 hours. This value exceeds the creep coefficient for wood construction of 2.0 specified in the Japanese Ministry of Construction Notification No. 1459 of 2000, so care must be taken when designing using this method.

However, the Building Standard Law in Japan requires that the creep adjustment factors for bending stiffness and shear modulus be clarified in the Japanese Ministry of Construction Notification No. 1446 of 2000. It has also been pointed out that the relative creep by Eq. (1) may overstate when applied to short-term data [6], and the creep tests should be continued to account for mechanosorptive deformation.

6. Trial design

In Chapters 3-5, basic data on the structural performance of this method were obtained through the joint tests, the full-scale tests, and the creep tests. In Chapter 6, we attempted to use these results to examine deflection under long term loading in the 11m span of this construction method. Here, the design conditions for this method within the scope of this study were the same as in the previous study [7], and the tree species composition was the same as in LM.

The results of the analysis showed that the deflection at mid-span of the analytical model was 4.38 mm. Multiplying this deflection by the deformation increase coefficient of 3.00 due to creep deformation caused by long-term loading and the deformation increase coefficient of 2.2 due to slip at the joints, the amount of long term deflection was determined to be 28.88 mm. This deflection is 1/381 of the 11m span, which is less than the deformation limit of 1/250 of the span. Therefore, it was confirmed that there is no problem with the use of the building within the scope of this study.

7. Conclusions

In this study, we proposed a parallel chord truss construction method using locally produced lumber. It uses three types of lumber in Mori-machi for each member in the right places and can be processed on standard lines of residential pre-cut processing machines. In addition, the joint tests, the full-scale tests, and the creep tests were conducted to verify the workability of this construction method and obtain basic data on structural performance for practical use. The results of this study are as follows.

- The simplicity of the construction method was confirmed through the fabrication of the specimens used in the tests.
- The joint tests were conducted for the bundle-chord joints using both drift pins and screws. The results showed that Japanese larch exhibited the highest strength characteristics for the middle type, while the mixed specification was between Japanese larch and Todo fir. The end type showed 70-80% of the middle type strength due to the tendency of the chord to crack. It was found that the strength and stiffness increased in proportion to the number of screws.

- The results of the full-scale tests showed that the final failure shape of each series was determined by one of three types of joints: a drift pinned joint with steel insert plate installed in the lower chord, a bundle-chord joint, and the lower chord end. Of these, the structural performance of the diagonal-chord joint at the lower chord end was found to be dominant for relatively short spans, while the structural performance of the drift pinned joint with steel insert plate and the bundle-chord joint was dominant for long spans.
- The results of the elastic analysis showed that the actual deflection in this method can be estimated by assuming that the deformation increase coefficient due to joint slip for the elastic deflection is 2.2 for the L series and 2.7 for the S series.
- The results of creep tests showed that the largest relative creep after 50 years (δ_{50y}/δ_0) was 3.00 estimated by Eq. (1) at mid-span deflection, which excluding data for less than 24 hours. This value exceeds the creep coefficient for wood construction of 2.0 specified in the Japanese Ministry of Construction Notification No. 1459 of 2000, so care should be taken when designing with this method.
- The results of the trial design confirmed that the deflection under long-term loading of this construction method in the scope of this study is less than 1/250 of the span, which is the deformation limit, and therefore, there is no problem with the use of the building.

Future work should consider creep coefficients for bending deflection and shear deflection, and further, the creep tests should be continued in the future to account for mechanosorptive deformation.

Acknowledgments

This research was commissioned by the Mori-machi Model Promotion Council (Chairman: Mr. Suguru Takada). We would like to express our sincere appreciation to the members of the Council, Mr. Kosuke Okajima, Mayor of Mori-machi, and all others involved for their invaluable cooperation in the development of this method and in conducting the tests. We would like to express our gratitude to them.

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Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine De Wolf,
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Paper Title: Study on a Development of Wooden Parallel Chord Truss Structure with Lumber in Mori-Machi, Hokkaido

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