World Conference on
Timber Engineering
Oslo 2023

R&D PROJECT FOR TECHNOLOGIES ABOUT MID- AND HIGH-RISE TIMBER CONSTRUCTION IN JAPAN

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ABSTRACT: The share of the timber construction per building area in the low-rise building was increased, but that in the mid- and high-rise building has never grown so much. Then, we conducted the R&D project for the technologies about mid- and high-rise timber construction in Japan. As a results, the performance evaluation method under the load duration of the wood-based composite components and the design method of the semi-rigid glulam frame jointed by drift pins with inserted steel plate were developed. The good results or the effective technical datum for the future implementation of the mid- and high-rise timber construction.

KEYWORDS: Duration of load, CLT panel construction, Design method for ultimate capacity of glulam frame

1 INTRODUCTION

The Act for Wood Use Promotion in Public Buildings was established at 2010 and revised as The Act for Wood Use Promotion to Contribute Realization of Carbon-Free Society at 2021. After 2010, the share of the timber construction per building area in the low-rise building was increased, but that in the mid- and high-rise building has never grown so much. Then, we conducted the R&D project for the technologies about mid- and high-rise timber construction in Japan. The summary of the following 4 themes which the project has focused on are reported in this paper;

1) The performance evaluation method of the wood-based composite components based on the element.
2) The ultimate capacity design of glulam semi-rigid frame and the possibility of the GLT mass timber.
3) The various performance evaluations of the mid-rise wood frame construction using the full-sized 6-story 2x4 testing building.
4) The studies on the simple structural design method for the CLT panel construction and the various performance evaluations using the full-sized test house.

2 PERFORMANCE EVALUATION OF WOOD-BASED COM-POSITE COMPONENT BASED ON ELEMENT

2.1 BACKGROUNDS

The performance evaluation methods for the I-joist which are provided as the designated building materials in Building Standard Law of Japan (hereinafter, "BSL") are specified in the Ministry of Construction Notification No. 1446 of 2000 as the methods based on only tests or that of estimating from the quality of the elements. However, the estimation methods were not clarified and rarely used for the accreditation of Minister of Land, Infrastructure, Transport and Tourism.

It is known that the performance under short-term load can be estimated from the performance of the elements employing the classical strength of materials method. But, it is unknown that those against long-term load can be estimated by the element.

2.2 COEFFICIENT OF DURATION OF LOAD

Therefore, as the one of the typical I-joist, that with 235 mm depth consist of the flange of LVL and the web of OSB were subjected to evaluate the coefficient of duration of load. The flange of 53 x 36 mm LVL, the web of 9.5 mm thick OSB and I-joist were subjected to the creep failure tests, as shown in Photo 1. As a result, the adjustment coefficient with respect to load duration of OSB, LVL and I-joist were 0.62-0.69, 0.73 and 0.72, respectively. The details of test conditions and results would be reported by Dr. R. Takanashi[1]. It was clarified that the adjustment coefficient with respect to load duration might be determined by those of elements whose failure occurred under the static load.

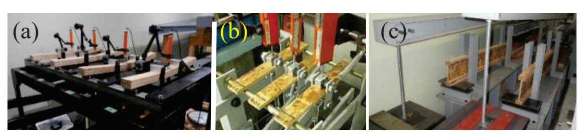

Photo 1: *Tests to evaluate the duration of load for (a) the flange of LVL, (b) the web of OSB and (c) I-joist.*

3. THE ULTIMATE CAPACITY DESIGN OF GLULAM SEMI-RIGID FRAME

3.1 BACKGROUNDS

In the high seismic country Japan, BSL requires that all buildings have to prevent to deform beyond the damage

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https://doi.org/10.52202/069179-0389

limit under the rarely occurred strong earthquake and that all building have to prevent to collapse under the extremely rarely occurred strong earthquake. In order to design the prevention of collapse, the designer needed to evaluate the ultimate capacity of structure.

3.2 SPECIMENS

Therefore, as one of the typical glulam semi-rigid frames, the estimation formula[2] of the drift pin joint with inserted steel plate was developed and verified in comparison with moment resisting joint tests on them. The specimens had variations in the diameter of pins, arrangements in rectangular or circle and the double or triple layouts, as shown Figure 1.

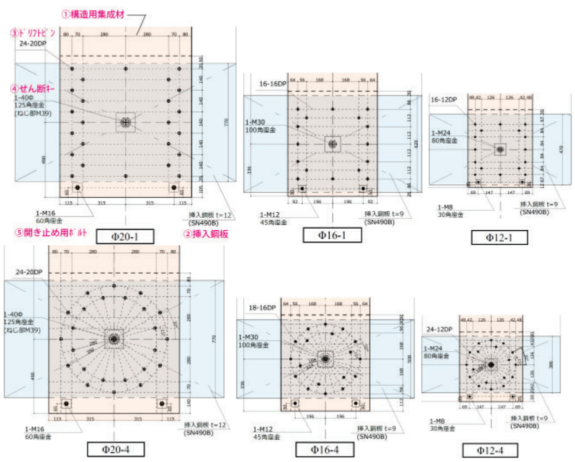

Figure 1: *Specimens of moment resisting joint of drift pins arranged in rectangular with inserted steel plate.*

3.3 TESTS AND RESULTS

The moment tests were conducted to them, as shown Figure 2. The positive and negative alternating load was applied to the top of specimen using an actuator and gradually increased to the failure of specimens. Several examples of the moment-rotational angle relations and typical fracture modes obtained by the tests were shown in Figure 3.

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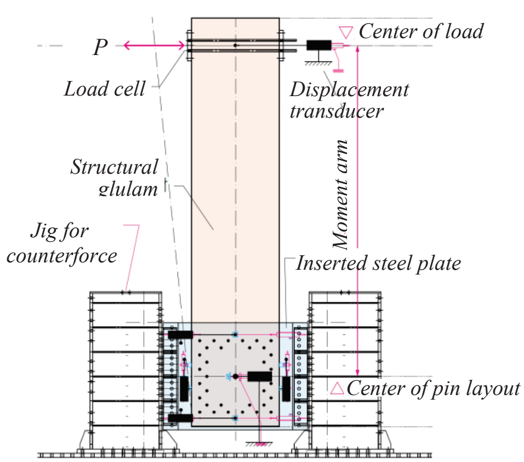


Figure 2: *Schematic diagram of the moment test for joint.*

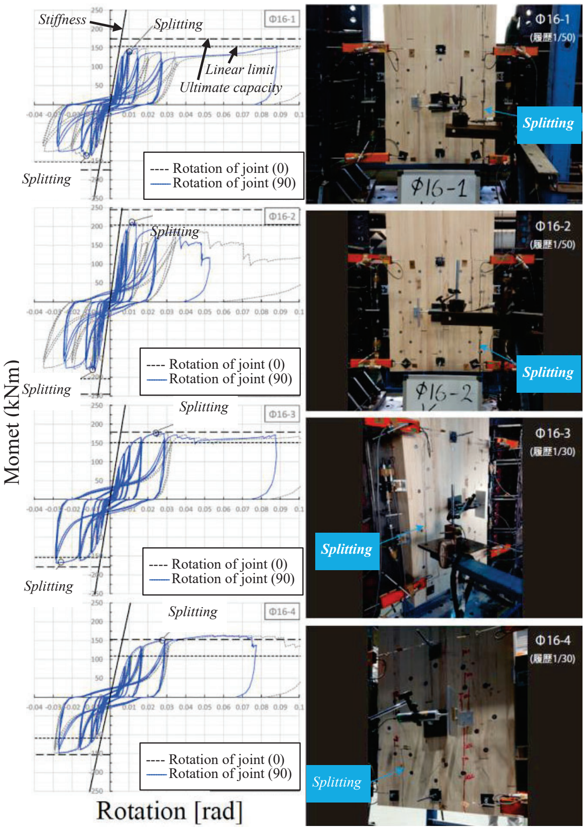


Figure 3: *Examples of* moment-rotational angle relations *and typical fracture modes of the moment test for joint.*

The plasticity factor μ was calculated from moment-rotational angle relations and compared with the depth of beam, as shown in Figure 4. Regarding the plasticity rate, the laminated timber thickness was 6.79 to 8.71 for 750 mm and 4.08 for 500 mm for the double circle, and the laminated timber thickness for the triple circle was 6.78 for 900 mm and 4.61 for 750 mm. Regarding the effect of the number of arrayed circles, the specimens with triple circle array tended to decrease the load earlier than those with double circles, resulting in a lower plasticity factor μ.

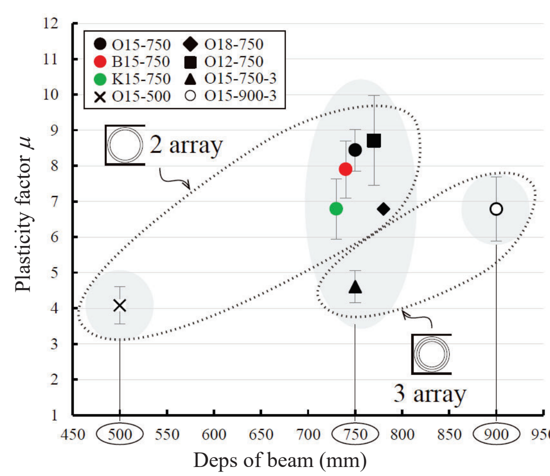


Figure 4: *Relationships between beam depth and plasticity factor μ.*

Then, the stiffness, the yield moment and ultimate moment calculated by the developed estimation formula [2] were compared with those obtained by the tests, as shown in Figure 5, 6 and 7, respectively.

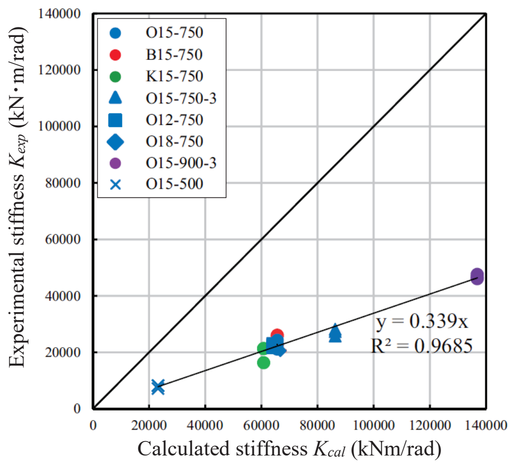


Figure 5: *Relationships between calculated and experimental stiffness.*

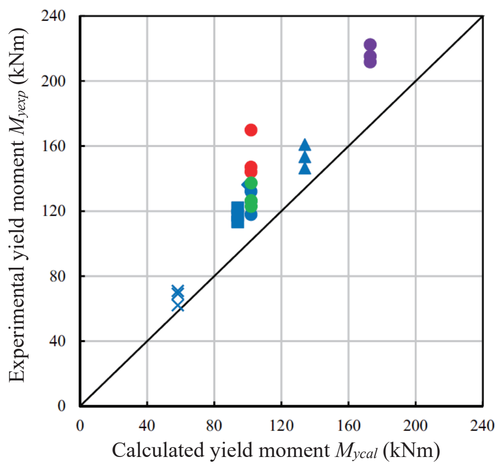


Figure 6: *Relationships between calculated and experimental stiffness.*

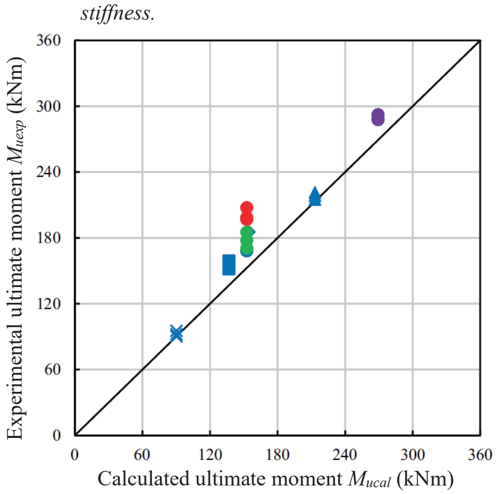


Figure 7: *Relationships between calculated and experimental stiffness.*

Regarding the possibility of estimating the rigidity, the ratio of the experimental value to the estimated value calculated assuming that there is no slip of the steel plate pin diameter + 1 mm tip hole is about 1/3. It was confirmed that the reduction rate indicated in the manuals was insufficient.

Regarding the estimation of yield strength, although Douglas fir was slightly higher, it generally showed high adaptability. It was suggested that a more rational evaluation method can be adopted than the method of setting the short-term allowable strength to 2/3 of the yield strength at which one of the connectors yields, which is written in conventional guidelines and manuals.

In addition, based on them, the evaluation method of the ultimate capacity for the semi-rigid glulam frame jointed by the drift pins with inserted steel plate were derived, and the validity was verified by the full-sized 2-story glulam frame as shown in Photo 2. Details are omitted due to space limitations.

Photo 2: *Tested full-sized 2-story glulam frame jointed by the drift pins with inserted steel plate.*

4 EVALUATION OF DUCTILITY FACTORS FOR TIMBER CONSTRUCTIONS

4.1 BACKGROUNDS

In high seismic country Japan, the ultimate capacity of building over a certain scale must be design under the extremely rarely occurred earthquake. In other words, it need be verified that the applied load or stress on the members, horizontal elements and joints under the base shear of 1.0 is not over the ultimate capacities of them. However, the applied load or stress can be decreased depending on the abilities of deformation. The factor indicating how much they can be decreased is called as Ds and provided in the Notification No.1791 of Ministry of Construction, 1980.

Although the Notification provides Ds according to the specifications of the frame and the L/D of joint, there is little technical knowledge on the relationships between the ductility of the joint or the frame and the Ds of the story. Therefore, these relationships were analysed numerically in this project.

Moreover, the Notification has never shown the Ds of the structure combined by parts with different ductility factor. Therefore, the Ds of the timber constructions combined by parts with different ductility factor were studied analytically in this paper.

https://doi.org/10.52202/069179-0389

4.2 NUMERICAL ANALYSES ON RELATIONS BETWEEN DUCTILITY OF JOINT AND GLULAM STRUCTURES

4.2.1 Analysis models

Three- and five-story semi-rigid frame, the brace and arch structure model in which elastic members are connected by rotation/axial springs were subjected to be analysed. Based on previous experimental data, three cases of high, medium and low capacity were set for the rotation / axial spring, as shown in Figure 8 as an example of a three-layer semi-rigid frame.

4.2.2 Analysis method

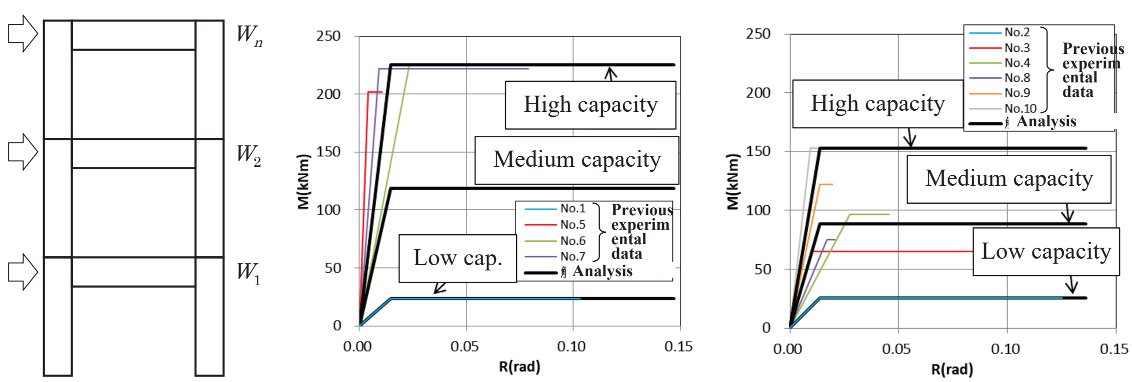
For the above-mentioned analysis models, (1) the pushover analyses were carried out, and the ductility factor of the structure, μs1 was obtained by applying the perfect elastoplastic model to the load-story drift curves with. (2) Nonlinear seismic response analyses were carried out, and the ductility factor of the structure, μs2 was obtained by the load-story drift curves. (3) The pushover analyses were applied to the contracted equivalent 1-DOF model of the analysis model, and the ductility factor of the structure, μs3 was obtained by the load-representative story drift curves.

4.2.3 Results and discussion

The relationships between the ductility factors of joint, μj set in the analysis models and those of structure, μs1, μs2, μs3 obtained by the analyses were shown in Figure 9(a), (b) and (c), respectively.

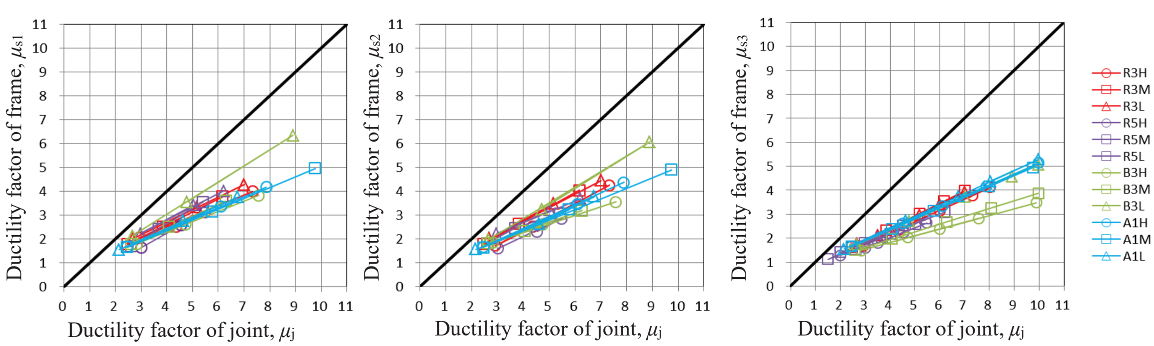
The semi-rigid frame, brace and arch structure model constructed by the joint with the 3-level capacity were subjected to the pushover analysis and others. As results of com-parison of the ductility factor of each structure calculated by the analyses with those of joint, the followings were obtained.

- The ductility factors of structure were usually lower than those of joints.
- The results of analyses on the contracted 1-DOF model were different from other 2 method of analyses.
- If the results of analyses on 3D model and the seismic response analyses were correct, the μ of arch would be lowest, the μ of semi-rigid frame would be relatively high, and the μ of brace would be various.
- Most of μs1 and μs2 were over the 0.5 x μ_j and below the 0.8 x μ_j, so the decreasing factor of seismic load under extremely rarely occurred earthquake may be able to be determined as the value of $(1.5 \times \mu_j - 1)^{-0.5}$ or more.



(a) Analysis model (b) Joint between post and beam (c) Joint at bottom of post

Figure 8: *Analysis model and restoring force characteristic of joints rotation spring.*



(a) Pushover 3D model *(b) Seismic response analysis* *(c) Pushover of 1-DOF model*

Figure 9: *Relationships between the ductility factors of joint and of structure.*

Notes: The legend of each plot is shown at the right end of (c), and its meaning is as follows. 1st letter shows the structure type of R: semi-rigid frame, B: brace and A: arch structure. 2nd figure shows the story of 3, 5 and 1. 3rd letter shows the joint capacity of H: high, M: medium, and L: low.

4.3 DUCTILITY FACTORS OF TIMBER CONSTRUCTIONS COMBINED BY PARTS WITH DIFFERENT DUCTILITY FACTORS

4.3.1 Analytical model and parametric study

From the past papers, the load-deformation relationships of the semi-rigid glulam frames, the shear walls, the brace systems and arch structure were picked up and modelled, as shown Figure 8. The vertical axis of it was normalised by the allowable capacity, Q_a. The semi rigid glulam frame was assumed as 3 variations with high, medium and low capacity. The shear wall was distinguished between the plywood and gyp-sum board. The brace system was distinguished between the glulam jointed by the drift pins with steel plate and jointed by the bolts. The arch structure was distinguished be-tween the curved glulam without joints and with some joints and straight glulam joint-ed by the drift pins. The ultimate capacity obtained by the bilinear model of the load-deformation relationships was defined as Q_u. The D_s of alone structure is no other than Q_a/Q_u. The D_s of medium glulam frame, SW with plywood and gypsum board and brace jointed by DP and bolts were 0.37, 0.609, 0.707, 0.505 and 0.244, respectively.

The combinations with variable load-deformation relationships, as mentioned above, were applied to the structural model which the summation of allowable capacity, Q_a is 1.0. The mixture ratio of the different load-deformation relationships was defined as β. The sum-mation of the ultimate capacity of the different structure, Q_u was varied from 0.2 to 0.75. The time history response analysis were con ducted to the structural model till the ultimate state.

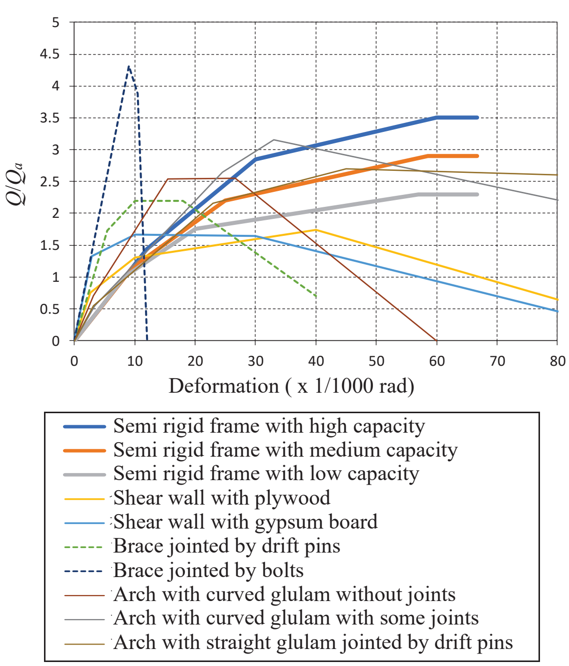


Figure 8: *The picked up and modelled load-deformation relationships.*

4.3.2 Result of parametric study

As a result of the parametric study, the response load-deformation relationships were obtained. When the maximum response deformation agreed with the ultimate deformation, the base shear was calculated by the results and defines as Cu. The Cu is no other than the ductility factor, Ds of combination structure after all. Some samples of Ds were shown in Table 1.

Table 1: *Examples of ductility factor Ds obtained by the analysis*

Glulam frame with medium capacity com-bined with		Shear wall with plywood	Shear wall with gypsum board	Brace jointed by drift pins	Brace jointed by bolts
Combi-nation ratio β	0	0.34	0.34	0.34	0.34
	0.1	0.34	0.34	0.34	0.29
	0.2	0.34	0.34	0.29	0.29
	0.3	0.31	0.29	0.30	0.52
	0.4	0.29	0.30	0.40	No solution
	0.5	0.29	0.30	0.41	
	0.6	0.29	0.29	0.43	
	0.7	0.29	0.30	0.45	
	0.8	0.30	0.35	0.48	
	0.9	0.35	0.37	0.49	
	1.0	0.35	0.40	0.50	

4.3.3 Conclusion

The ductility factor of timber constructions combined by parts with different ductility factor need to adopt the higher one. However, the case of combination with shear wall had a possibility to decrease the ductility factor still more.

5 6-STORY 2X4 TEST BUILDING

5.1 BACKGROUNDS AND OBJECTIVES

In Japan, there were few construction examples of the mid- and high-rise wood frame construction. High-capacity shear walls and fire-resistant structures have been developed for the mid- and high-rise buildings, however, they have never been constructed actually using them together. In addition, it was necessary to evaluate the performance of each part because the mid- and high-rise buildings were subject to heavy rain and winds, and flat roofs, which had not been implemented for low-rise buildings, were also constructed.

5.2 WORKABILITY

The test building was built in BRI (Photo 3) was completed in 2016 and employed the large amount of gypsum boards in order to satisfy the fire requirement by BSL. The construction of the frame wall construction is to lift and install the frame panels produced in the factory with the crane. The number of man-hours for each process was measured from the number of working days and the number of workers. It took a total of 100 working days and 666 manpower to construct the construction. The number of days and man-hours for each procedure were shown in Table 2. The workability of 0.14 man/m^2 is

https://doi.org/10.52202/069179-0389

about the same as the construction efficiency of a low-rise light frame construction house, but for a medium-rise building, 0.07 man/m^2 is required for marking to ensure construction accuracy. As a result, accuracy of 1 to 1.5/1000 was confirmed both horizontally and vertically after the completion of the framework construction.

This 6-story test building has two-hour fire resistance specifications (triple thick reinforced gypsum boards) on the 1st and 2nd floors, and one-hour fire resistance specifications (double one) on the 3rd to 6th floors. It took 252 man-days to install the large amount of gypsum boards, and they accounted 1/3 of total man-hours, as shown in Figure 10.

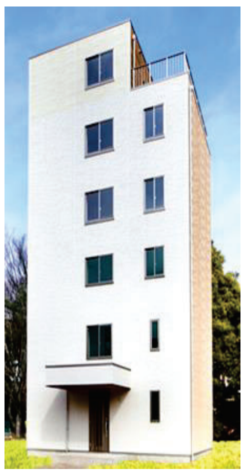


Photo 3: *6-story 2x4 testing building in BRI.*

Table 2: *The number of days and man-hours for each construction procedure*

Procedure	Actual working days	Man-hours	Man-hours required: Per floor area	Man-hours required: Per story	Remarks
Foundation	26	85	0.42		
Scaffold	6	19	0.09	3.17	Divided into 6 times
Wooden framework		43	0.21	7.17	
Wood framework	13	28	0.14	4.67	
Accuracy management	12	15	0.07	2.50	Marking and others
Fixture working	47	80	0.40	13.33	Stairs, sashes, etc.
Gypsum boards		252	1.25	42.00	
External	17	68	0.34	11.33	
Inside	27	124	0.61	20.67	
Openings	4	4			
Lifting	10	56			9 times*
Sidings		104	0.52	17.33	3 times*
Total	100	666	3.30	111.0	

Note: *: using high place work vehicle

5.3 SINKAGE

The sinkage due to further drying of dimension lumbers or the creep behaviour under the dead and live load is one of the important problems on mid-rise 2x4 construction. It was measured by the displacement transducer set at the end of the wire which was hang from each story to the base, as shown Figure 11.

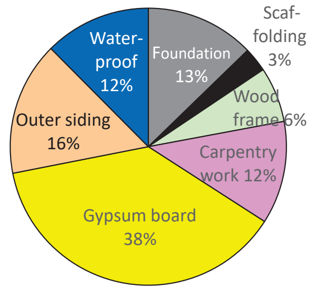
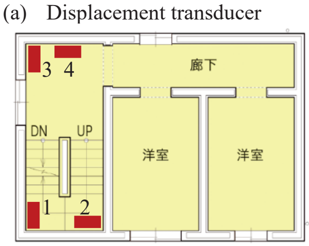


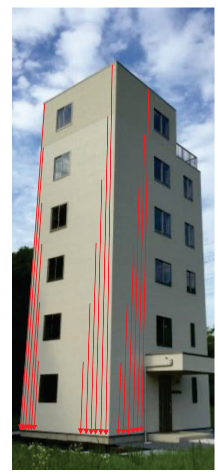
Figure 10: *Distribution of working time of each process.*

Among the measurement results of the sinkage, the measured value of No. 4 is shown as a typical example in Figure 11. It was gradually increased within 1 mm per story, but settled down over 1 year after.

(a) Displacement transducer



(b) The position of sensors (1-4)



(c) Image of wires

Figure 11: *Measuring methods of sinkage.*

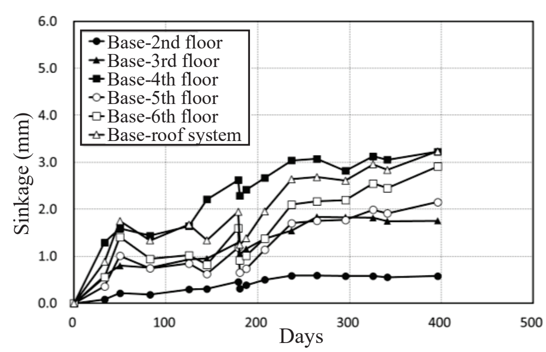


Figure 12: *Sinkage of 6-story 2x4 construction.*

5.4 VERIFICATION OF WATERPROOFING OF FLAT ROOF

The flat roofs are often used for the roofs of mid-rise wooden buildings. Moisture, such as rainwater, acts before waterproofing construction and may be confined by waterproofing layer. Contained moisture conditions that are maintained for long time are likely to cause biodegradation of the structural members.

https://doi.org/10.52202/069179-0389

Therefore, a grid-like ventilation groove was provided in the insulation material to be installed on the roof base material, and this groove was used to discharge moisture from the roof base material to the outside from the deaerator, as shown Figure 13. The water was intentionally sprinkled on the flat roof before waterproof, as mentioned above. The humidity sensors were installed near the grooves of the insulation at every 1 m from the deaerator to measure the humidity continuously. On the other hand, the flat roof balcony without deaerator was subjected to measure the humidity near the grooves of the insulation as a control.

The relative and absolute humidity under the waterproof layer of the flat roofs and the roof balconies decreased regardless of the presence or absence of the deaerator. The humidity of the flat roof with the deaerator reduced faster than the roof balcony without the deaerator. It was clarified that the deaerator installed at the flat roof contributed to the improvement of the moisture emission rate.

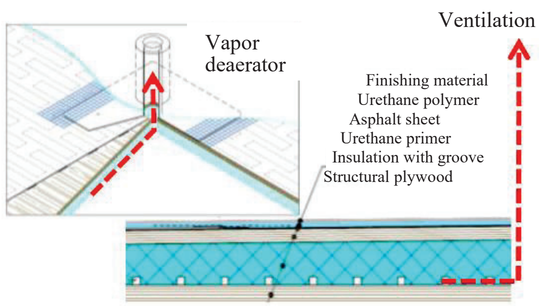


Figure 13: *Vapor deaeration and ventilation system of flat roof*

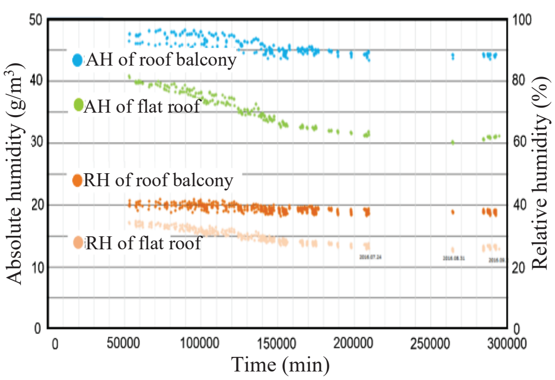


Figure 14: *Time history change of absolute and relative humidity at the flat roof with deaerator and the roof balcony without it.*

5.5 CONCLUSIONS OF 6-STORY 2X4 TEST BUILDING

Through the constructing the 6-story 2x4 test building and the trials to evaluate the various performance, results are summarized as follows:

- The workability of 6-story 2x4 construction is about the same as the construction efficiency of a low-rise light frame construction house.
- The man-hour to install the many gypsum boards accounted 1/3 of the total.
- The sinkage was gradually increased within 1 mm per story, but settled down over 1 year after.
- The deaerator installed at the flat roof contributed to the improvement of the moisture emission rate.

In addition to those, the good results or the effective technical data for the future studies were obtained by the measuring of the seismic response under strong ground motion[3], the water-proof performance of window sash in higher story, the floor impact sound insulation[4] and others.

6 CLT TEST HOUSE

The 2-story CLT test house, as shown in Photo 4, was built in BRI for the experimental construction and the various performance evaluation of the CLT panel construction which had little experienced in Japan. The good results or the effective technical data for the future studies were obtained by the measuring of the dimension stability and the mechano-sorptive deformation of CLT panel, the air tightness, the desorption behaviour of the humid shut in the waterproof layer, the floor impact sound insulation and others.

Photo 4*. 2-story CLT test house in BRI.*

7 CONCLUSIONS

As mentioned above, we have conducted the R&D project for technologies about mid- and high-rise timber construction in Japan in order to grow up the share of the timber construction in the mid- and high-rise building. The results are summarised as follows:

- Through the creep fracture tests on the I-joists and their elements, the adjustment coefficient with respect to load duration of the I-joist might be determined by those of elements whose failure occurred under the static load.
- The developed estimation formula of the yield and ultimate capacities of the moment resisting joint using the drift pin with inserted steel plate was verified by the moment tests on them.
- As the results of the numerical analyses on the relations between ductility factors of joint and glulam structures, it was clarified that the ductility factors of the semi-rigid frame was lower than those of their joints generally, the results of pushover analysis with 1-DOF model were different from those with 3D

https://doi.org/10.52202/069179-0389

model and seismic analysis and the results of the nonlinear seismic response analyses, and others.

- As the results of the ductility factors of the timber constructions combined by parts with different ductility factors, it was clarified that such construction needed to adopt the higher one. However, the case of combination with shear wall had a possibility to decrease the ductility factor still more.
- Through the constructing of 6-story 2x4 test building and the measuring of various performance of it, the results are summarised in section 5.5.

ACKNOWLEDGEMENT

A part of this research was funded by the Public/Private R&D Investment Strategic Expansion Program of Cabinet Office. The studies on 2x4 and CLT testing building were conducted as one of the collaborative research with Japan 2x4 Home Builders Association and Japan CLT Association, respectively. We would like to thank the people concerned.

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