

# Static and Dynamic Properties of Portal Frames Composed of Built-Up Sawn Square Timber

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## Abstract

In order to propose an alternative structural element to be used for wooden dwelling houses in rich forest area, we paid attentions to a portal frame structure which is composed of not glulam but built-up members whose raw materials are dried sawn timbers taken from plantation grown forest. For establishing design procedure of the structural element, we made two different types of portal frames and conducted, at first, basic dynamic test to estimate natural frequency and dumping factors by fixing small shake excitation machine on the portal frames, then static push-pull cyclic loading tests were conducted until failure. The natural frequency of both portal frames was almost same but the higher order frequencies were likely to be affected by the difference of shear reinforcement of built-up members by hardwood dowels. While on static properties, as both portal frames failed in brittle manner due to bending failure at column or tear off at connection plate made of compression wood, further improvement of connection system was required for obtaining more stable alternative elements to glulam.

**Keywords:** Sawn timber, built-up beam, dowel, compression wood, portal frame.

## Introduction

This research aims to propose an alternative wooden portal frame system in which glulam and steel fasteners are not intentionally used but solid sawn dried timber and wooden fasteners are only to be used. These restrictions were brought from the condition that the general theme of the project was involved in a site-study in Shiga prefecture where no glulam factory but rich forest resources existed, hence utilization of solid timber taken from the provincial forest was an importance research purpose. In order to realize this purpose, at first we developed new type of dowel joint which has not only shear resistance but also axial resistance like bolted joint. Next subject was to develop a joint system for connecting beam and column member without using steel fasteners for rotational moment. As we had to use sawn square timbers for portal frame structure, beam and column members were composed of two layered composite beam or column for obtaining sufficient flexural rigidity. In addition to this, we adopted "Kamatsugi" (Japanese traditional parallel member joint) for getting long span members. In consequent, the portal frame became quite complicated structure, thus we used FEM to predict static as well as dynamic performance of the portal frame composed of complex members. Finally, static and dynamic experiments were conducted to make it possible to compare with FEM results.

## Materials and Methods

### Development of Wedge-Split-Dowel (WSD)

Figure 1 shows a concept of "Wedge-Split-Dowel (WSD)" (denote as WSD hereafter) and how WSD could be worked as a fastener for two layer built-up member. Japanese White Oak (*Quercus myrsinaefolia* Bl.) of 30 mm diameter and 280 mm length was use as dowel.

Slit of 40 mm depth was cut on both ends of dowel. Inserting a wedge made of Japanese Oak (*Quercus crispula* Bl) slightly into the bottom slit, dowel is pushed into the lead hall whose ends are conically widened using a special drilling bit having a pair of cantilever edge which can expand using centrifugal force.

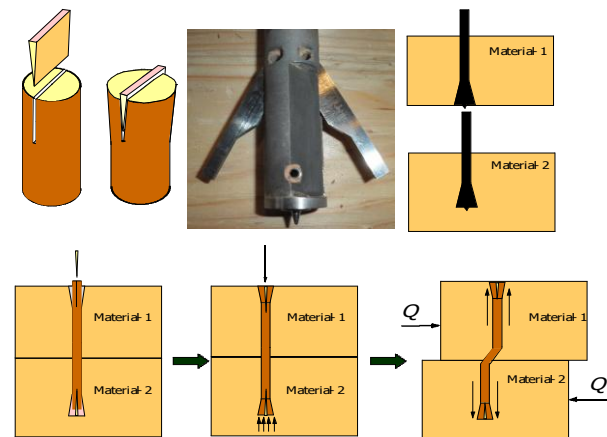


Figure 1. Concept of "Wedge-Split-Dowel (WSD)".

Once end of wedge reached at bottom of lead hall, dowel was hammered until its bottom end could be expanded by insertion of wedge. Another dowel end was also expanded in the same manner.

This method was developed by imitating Japanese traditional carpenter technique called as "blind wedge-split tenon technique". By applying this WSD to a two layered built-up timber member, not only initial slip between two layers, but also ultimate horizontal shear strength of composite member was expected to be improved by the axial resistance due to expanded edges.

### Shear Resistant Test of WSD

Figures 2 and 3 indicate test set-up for evaluating shear resistance of single WSD.

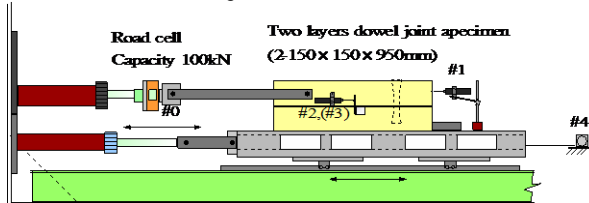


Figure 2. Test set-up for WSD jointed specimen.

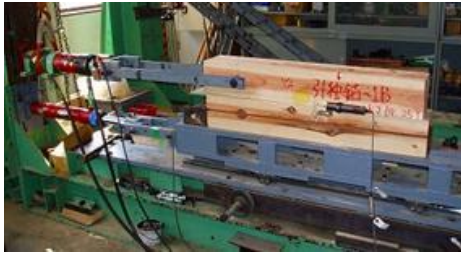


Figure 3. Actual feature of shear test.

For the main members, 145 mm squares of sawn solid timbers of Japanese Cedar (*Cryptomeria japonica* D.Don) taken from a provincial area, in which dominant research project over this research was involved, were used. Average density of the specimen was 419 kg/m<sup>3</sup> and average moisture content was 18.2%. Three replications were prepared for this shear test. Relative slip displacement between two layers was measured using displacement measuring devices denoted as #2 and #3 in Figure 2, while shear resistance force was measured with load cell denoted as #0.

### Flexural Test on Built-Up Beams

In order to make sure the effect of “Kanawatsugi” and WSD on the flexural performance of built-up members, two different types of built-up beams were fabricated using members which were connected to longitudinal direction

with “Kanawatsugi” joint and built-up using WSD at both ends. The Beam-1 was not reinforced, while the Beam-2 was reinforced with WSD at the part of Kanawatsugi-joint. Two composite beams of 2250 mm long were loaded at center point until failure. Figure 4 shows features of flexural experiment. The materials used were Japanese Cedar who dimension and physical data were the same as those used in WSD shear resistance test.

### Development of Compressed Cross Laminated Plate (CCLP)

Based on the preliminary test results, we developed a new type of wooden gusset plate made of three layered cross laminated epoxy-glued timber plate using 130 degree hot-press compression process for obtaining high-density, strong and isotropic wooden gusset plate of 15 mm thick for the connection between beam and column composite members. Figure 5 indicates “Compressed Cross Laminated Plate” (denotes as CCLP hereafter) and configuration of beam-column joint using double CCLP gusset plates with 18 mm dowels made of Japanese White Oak (*Quercus myrsinaefolia* Bl.).

### Static Push-Pull Cyclic Loading Test on Composite Portal Frame Specimen

Figure 6 shows test set-up of two-hinged portal frame specimen subjected to a static cyclic push-pull horizontal load and actual feature of the experiment. Test specimens were fabricated using the same kind of members as those used in the bending test. Span length was 2542 mm and height was 1830 mm.

### Dynamic Test of Portal Frames Using Portable Shake Excitation Machine

Figure 7 shows a set-up of dynamic test and close-up view of portable shake excitation machine (DTH-500-30, Asahifactory Corp.) fixed on the top surface of the beam member using four lag-screws.

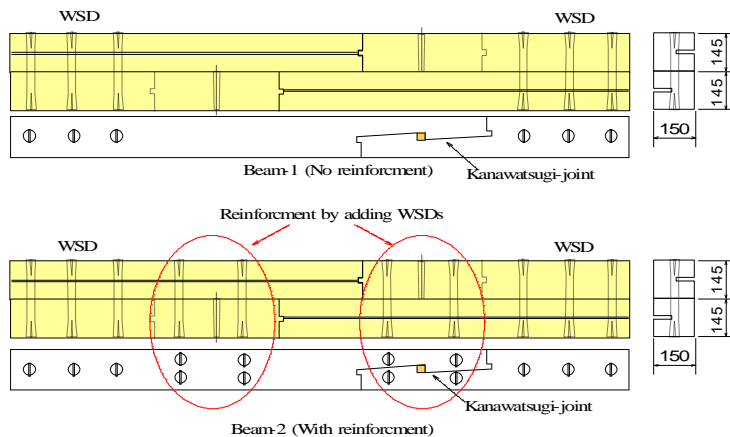


Figure 4. Configurations of built-up beams and actual feature of the bending test.

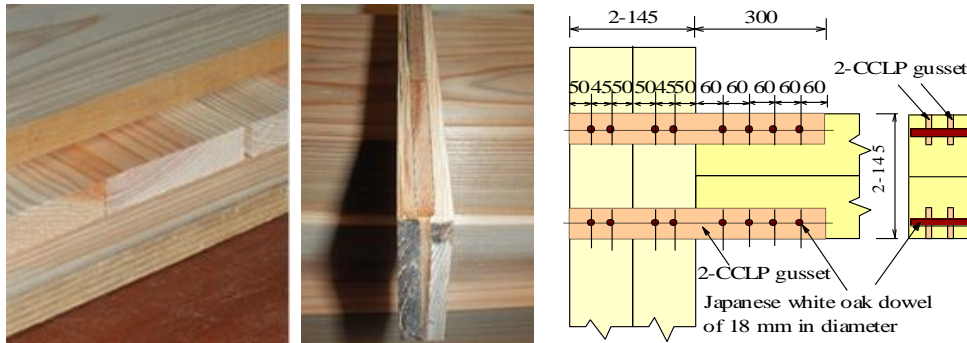


Figure 5. Features of CCLP produced and configuration of beam-column joint.

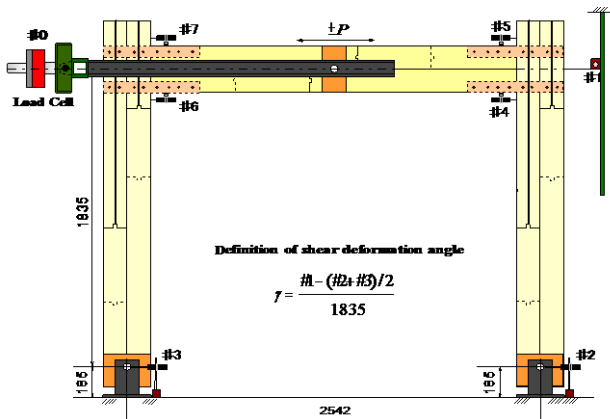


Figure 6. Test set-up of portal frame specimen and actual feature of the experiment.

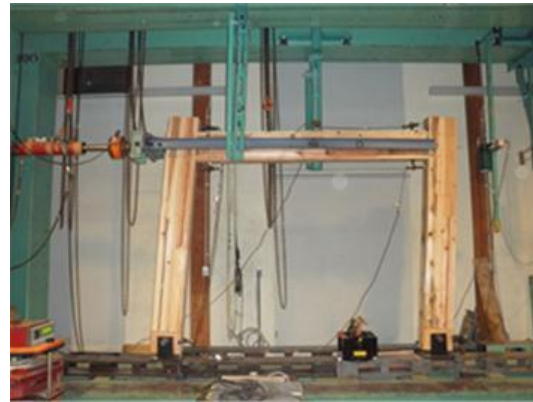


Figure 7. Test set-up of dynamic test and close-up of portable shake excitation machine.

At first a sine-sweep excitation test was done by inducing sine wave action starting from 1mHz till 10Hz within 6 min to detect a dominant frequency. After tentatively determining apparent natural frequency by using a spectrum analyzing software (SPCANA Ver.4.9 distributed by Prof. N. Kamata, Fukuyama Univ.), constant shaking test was done using the apparent natural frequency for a meanwhile, then the machine was suddenly switched off so as to let the portal frame vibrate as freely until naturally stop due to damping effect. Data taking from this free vibration part was inputted into another software (Free Vib distributed by Prof. N. Kamata, Fukuyama Univ.) to estimate damping factor by the curve fitting method.

### Mechanical Models of Joints and FEM Analyses of Portal Frames

**Mechanical Model of WSD.** As WSD has some amount of axial resistance due to inclined embedding action at expanded ends, axial stiffness was evaluated as shown in equation (1) by referring lizuka's previous study (lizuka1978), where

$$K_t = \frac{E_\theta(\pi DL)}{\alpha} \left\{ \frac{\sin^2 \theta + \mu \sin \theta \cos \theta}{\cos \theta} \right\} \quad (1)$$

$$\alpha = 31.6 + 10.9D, E_{\theta} = \frac{E_0 E_{90}}{E_0 \sin^2 \theta + E_{90} \cos^2 \theta} \quad (2)$$

$\mu$  : friction coefficient between dowel and softwood timber.  
Other parameters involved in the equations (1) and (2) are referred to Figure 8.

**Apparent Slip Modulus ( $K_s$ ) of Hardwood Dowel with Double CCLP Gusset Plates.** As can be seen from Figure 5, rotational rigidity at beam-column joint of the portal frame depends on the slip modulus between hardwood dowel and double CCLP gusset plates. For estimating this value, a nonlinear FEM program developed for drift-pined joint with steel gusset plate (Komatsu 1988) was used as shown in Figure 9. In this study, CCLP was assumed as a rigid body and elastic constants of steel drift pin were replaced by those of hardwood dowel (AIJ 2009) but strain hardening rule after yielding of steel was used as it is because nonlinear behavior was not concerned in this study.

**FEM Modeling of Portal Frame.** Figure 10 shows a schematic implementation how actual complicated structure was approximated using FEM model. Joint stiffness of Kamatsugi-joint, WSD shear and axial direction, slip modulus between hardwood dowel and CCLP gusset plate were approximated by spring element. Sawn timber and CCLP gusset plate were approximated by beam element.

An eccentricity between member axis and gusset plate one was modeled by introducing beam element whose elastic constant was assumed as  $1 \times 10^7 \text{ kN/mm}^2$ . Figure 11 shows a FEM model of whole portal frame.

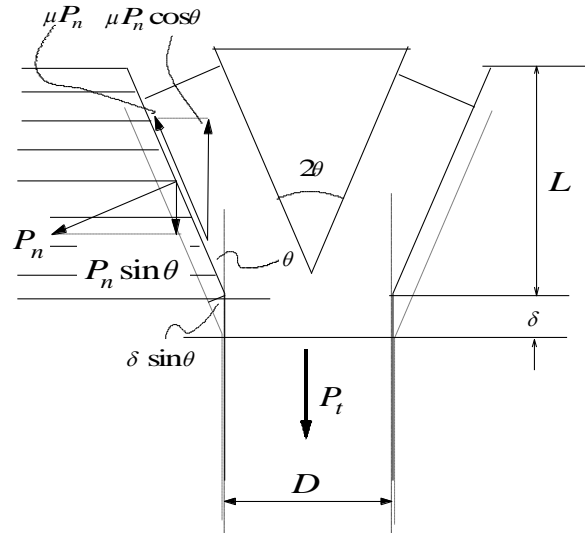


Figure 8. Mechanical model of WSD.

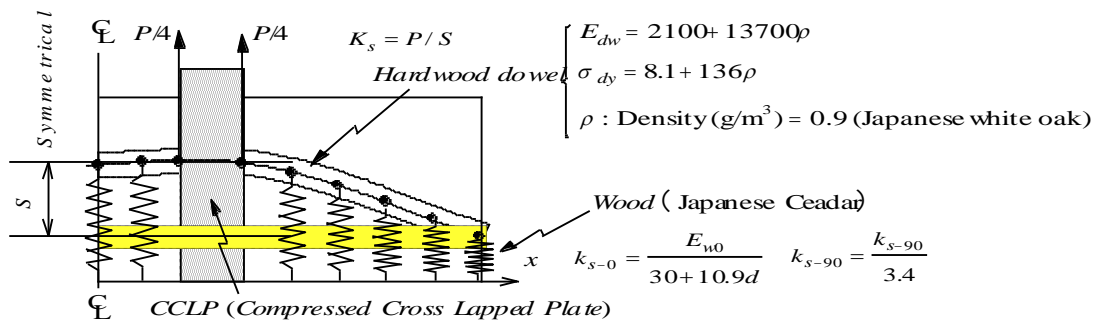


Figure 9. FEM model for estimating slip modulus between hardwood dowel and double CCLP.

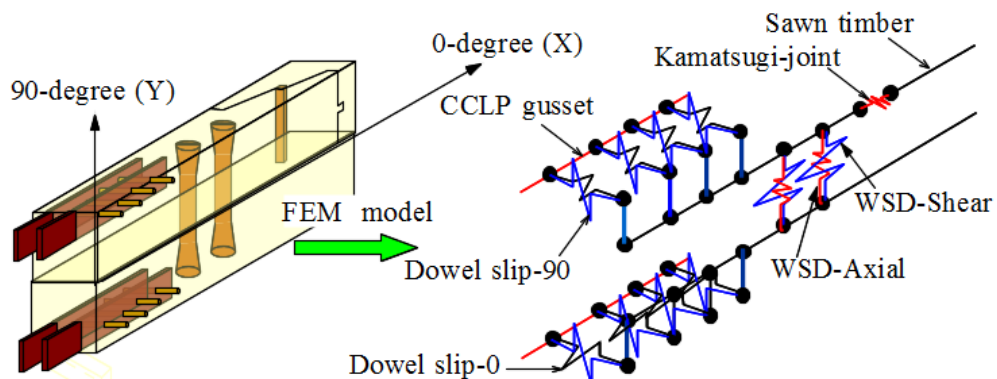


Figure 10. Schematic implementation how actual complicated structure was approximated using FEM model.

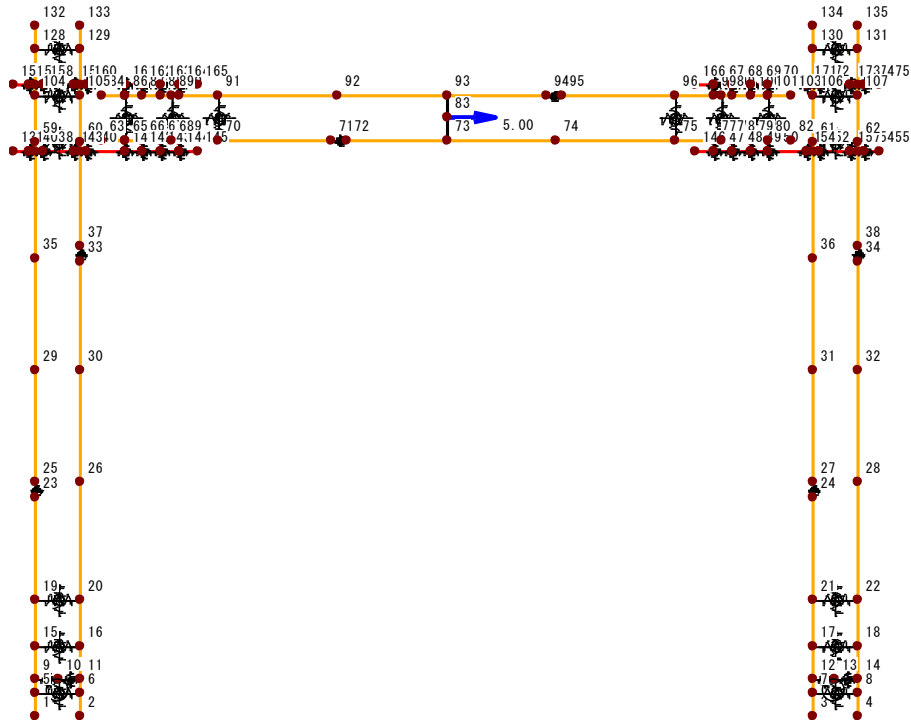


Figure 11. FEM model of whole portal frame (non- reinforcement type).

## Results and Discussion

### Performance of WSD

Figure 12 shows shear force ( $Q$ )-relative slip ( $S$ ) relationship of WSD joint and its typical failure phenomena. Table 1 shows axial and shear stiffness of WSD.

### Effect of WSD on the Flexural Performance of Built-Up Member

Figure 13 shows comparisons of flexural performance of Beam-1 without reinforcement and Beam-2 with reinforcement at Kanawatsugite-joint by 2-rows of WSD.

Initial stiffness was 33% and ultimate strength was 21% increased respectively by the reinforcement.

### Results of Static Loading on Portal Frames

Figure 14 shows comparisons between experimental results and FEM calculation for the case of PF-2 (No reinforcement). Solid line and circle plot indicates shear force ( $P$ )-deformation angle ( $\gamma$ ) relationship calculated by FEM. Solid line with diamond plot indicates brittle failure load predicted using equation (3) where bending, shear and axial forces were all considered.

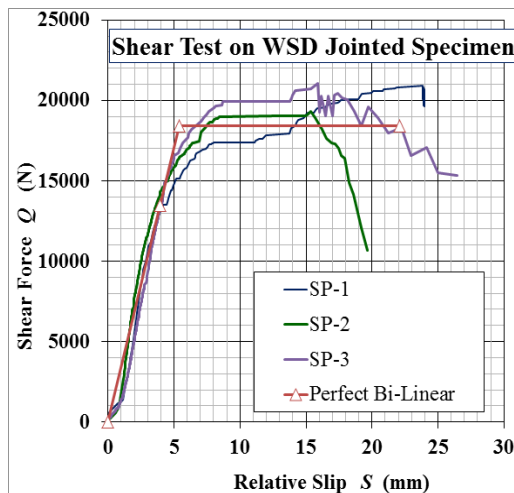


Figure 12. Shear force ( $Q$ )-relative slip ( $S$ ) relationship and failure phenomena.



a) Large deformation of dowel



b) Tear-off of the dowel

Table 1. Axial and shear stiffness of WSD and elastic constant of Japanese Cedar used.

$K_y$ [Axial : eqs.(1),(2)]	3.50kN/mm	$E_0=7\text{kN/mm}^2$ , $E_{90}=0.28\text{kN/mm}^2$ , $D=18\text{mm}$ , $L=50\text{ mm}$ , $\theta=0.1$ ,
$K_x$ [Shear : experiment]	3.42kN/mm	$\mu=0.4$

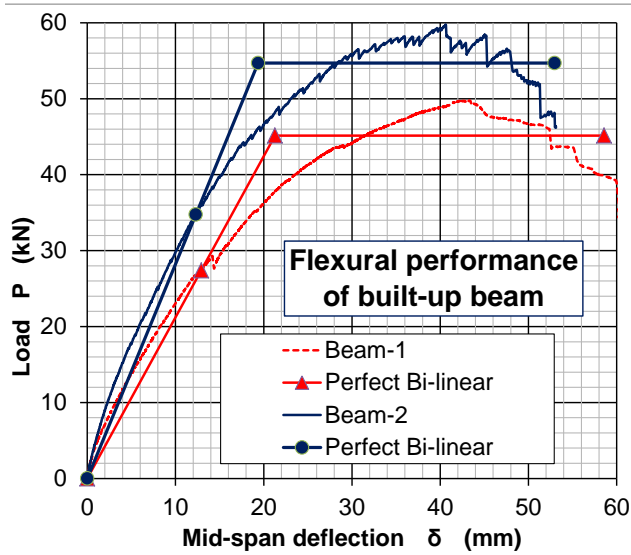


Figure 13. Load ( $P$ )-deflection ( $\delta$ ) relationship and failure phenomena of built-up members.

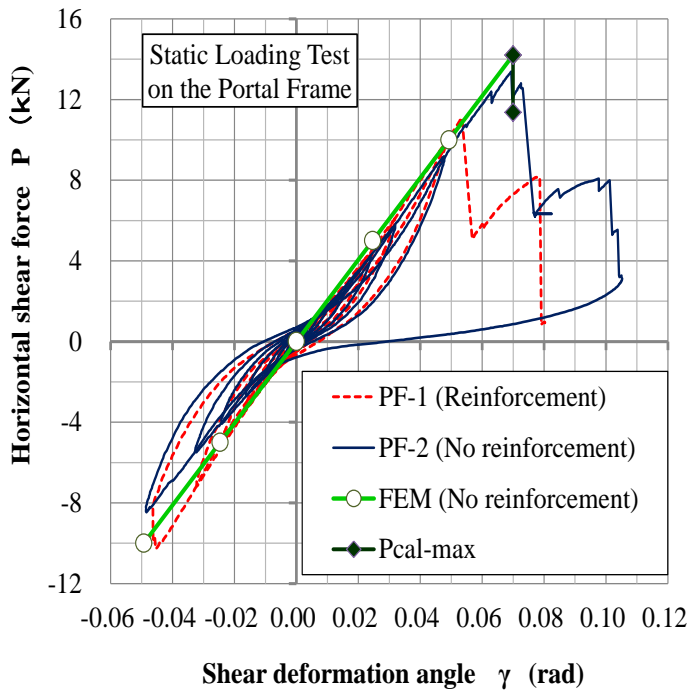


Figure 14. Comparisons between experimental results and FEM result with failure phenomena.

$$\frac{\sigma_b}{F_b} + \frac{\sigma_t}{F_t} + \frac{\tau_s}{F_s} = \frac{M_{\max} / Z_e}{F_b} + \frac{N_t / A_e}{F_t} + \frac{1.5Q_s / A_s}{F_s} \quad (\text{in N, mm unit}) \quad (3)$$

$$= \frac{(2090000 / 402979)}{22.2} + \frac{(450 / 16638.75)}{13.5} + \frac{1.5 \times (9020 / 16675)}{7.0} = 0.352$$

where,

$\sigma_b, \sigma_t, \tau_s$ : working bending, tensile and shear stresses calculated by FEM at  $P=5\text{kN}$ , respectively.

$F_b, F_t, F_s$ : tabulated characteristic bending and tensile strength values for Japanese Cedar (AIJ 2006), while for the shear strength value was quoted from our original experimental result (Kitamori *et al.* 2012) as tabulated value was too low compared with actual observed values.

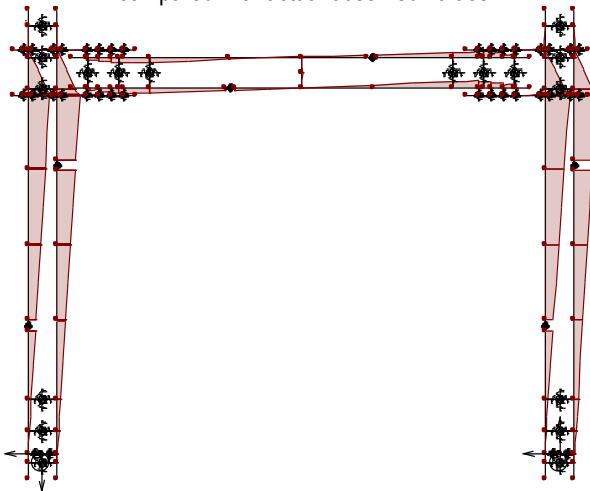


Figure 15. Bending moment diagram of portal frame PF-2 calculated by the FEM.

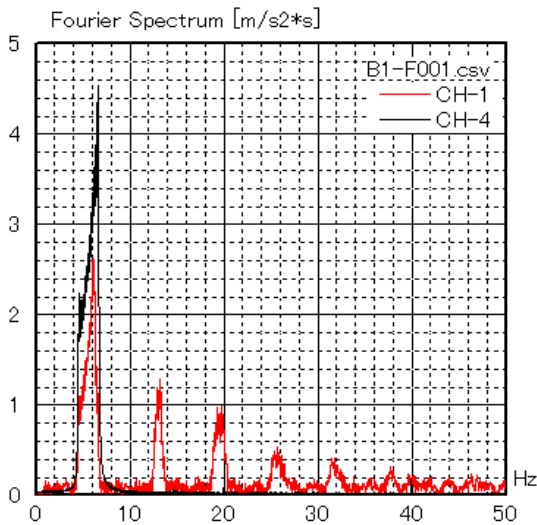
In equation (3), ratio to 1.0 was 2.845; therefore critical load was estimated as  $P_c = 5 \times 2.845 = 14.2 \text{ kN}$ . Comparison between predicted failure value and observed one in Figure 14 indicates that a good agreement was obtained.

Figure 15 indicates a bending moment diagram of portal frame PF-2 calculated by the FEM in which red-circle indicates point of critical bending moment in column member.

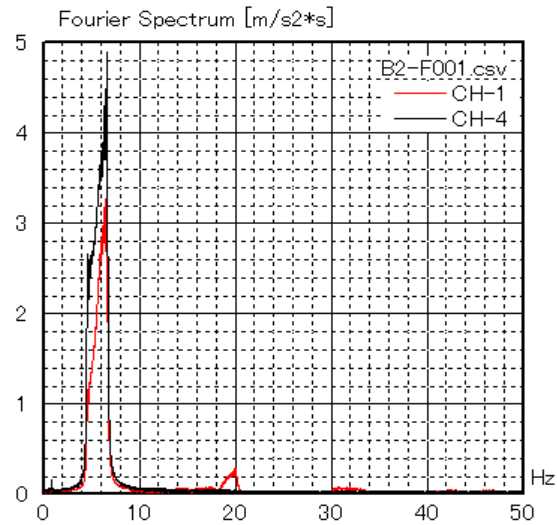
### Results of Dynamic Test on Portal Frames

Figures 16(a) and (b) show spectrum diagrams of specimen (a) for PF-1 and (b) for PF-2 observed by sine sweep test. Natural frequency of both specimens was 6.4Hz, although for non reinforced PF-1, a lot of peaks were observed which thought to be higher order frequencies. While figures 17(a) and (b) show free vibration phenomena obtained after forced vibration test with a constant frequency of 6.4 Hz then stopping portable shake excitation machine suddenly to estimate the damping factors. Damping factor estimated for both specimens was also same as 2.4%.

It was deduced from these interesting results that the reason, why dynamic properties were just the same, in spite of the fact that PF-2 was reinforced at Kamatsugi-joint part by additional WSD, might be implemented that the mechanical properties of portal frames were rarely affected by member's partial stiffness but might be strongly dominated by the performance of beam-column joints which had the same mechanical property for both specimens.



(a)



(b)

Figure 16. Spectrum diagrams of PF-1 for (a) and PF-2 for (b).

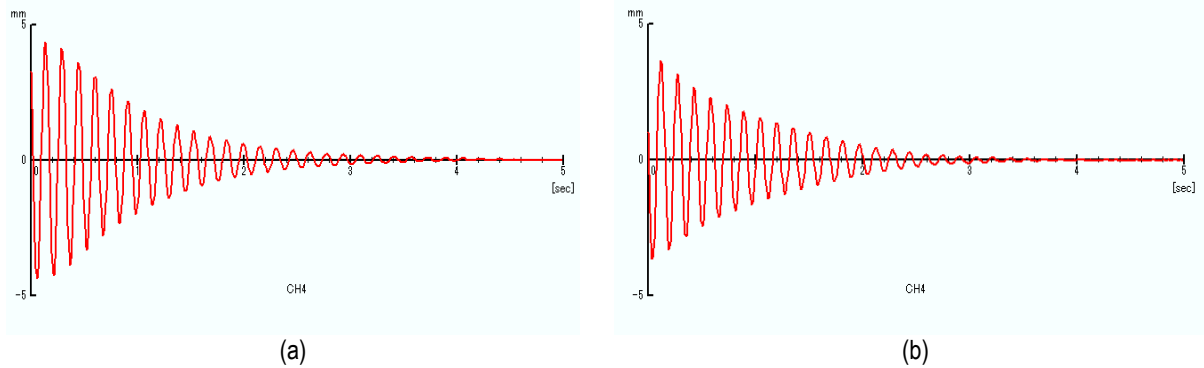


Figure 17. Free vibration curve of PF-1 for (a) and PF-2 for (b).

### Conclusions

In this study, we tried to estimate static and dynamic properties of quite complicated built-up portal frame specimens, which were made of artificially dried Japanese Cedar sawn timber of 145 mm square cross section with artificial saw-cut on one surface for preventing drying checks and jointed longitudinally using traditional carpenter's technique called as Kamatsugi-joints. In order to understand behavior of this kind of complicated wooden structure in precisely, we tried to establish a quasi-3D semi-rigid wooden portal frame mechanical model as finely as possible by employing a commercially available FEM program. Thus we took, every kind of existing stiffness of joints such as Kamatsugi-joint, wedge-split-dowel (WSD) joint, splice joint with hardwood dowel and double compressed cross laminated plates (CCLP), into considerations based on experimental observation or theoretical modeling. In consequence, comparisons between FEM calculation and experimental observations were not so bad at least for non reinforced type specimen thus the FEM modeling was thought to be reasonable.

### Acknowledgments

This research was fully supported by the research program called as "Mobile Site Type Research on Sustainability Science-Shiga Site Research" provided by the Institute of Sustainability Science (ISS), Kyoto University. Authors would like to express their sincere thanks to the ISS for the financial support. Authors also would like to express their appreciation to Mr. Ryo Futami for his technical support during portal frame tests.

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