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STATIC AND DYNAMIC LOADING TESTS OF BRACKET COMPLEXES USED IN TRADITIONAL TIMBER STRUCTURES IN JAPAN

Kaori FUJITA[1], Isao SAKAMOTO[2], Yoshimitsu OHASHI[3] And Masahiko KIMURA[4]

SUMMARY

The bracket complex is a kind of bearing system, usually located on the top of a column supporting the long eaves and roof, transmitting the vertical load of the heavy roof to the column. It is often used in Buddhist temples and Shinto shrines of traditional timber structure. The bracket complex, being a combination of timber blocks, is said to have positive effect on the seismic performance of traditional timber structures, but this fact has not been proved theoretically nor quantitatively. The aim of this paper is to examine the seismic performance of the bracket complex and the effect it shows on the whole structure, through experiments and analyses. Static lateral loading tests and shaking table tests were conducted on four different types of bracket complex. The stiffness, natural frequency and load displacement relationship were determined. A structural model of the bracket complex is proposed. The stiffness of the model is determined by the theoretical elastic deformation perpendicular to the grain of wood and by friction coefficient of the specimen. Response analyses were carried out with the proposed structural model, using the acceleration record measured during the 1995 Hyogoken-Nanbu Earthquake. The results of the simulation and the shaking table tests were discussed in comparison.

INTRODUCTION

The bracket complex is a kind of bearing system usually located on the top of a column supporting the long eaves and roof, transmitting the vertical load of the heavy roof to the column. It is said to have been first introduced to Japan from China in the 6th century AD, when Buddhism first reached our country. The bracket complex is often used in Buddhist temples and Shinto shrines.

The characteristic of the Japanese traditional timber structure is their large deformation capacity and their high damping effect. The bracket complex is said to have positive effect on the seismic performance of traditional timber structures, but this fact has not been proved theoretically nor quantitatively.

SPECIMEN

Four most fundamental types of bracket complexes were selected as specimens. The names of the specimens and the names of the types of the brackets are as follows, K1:*Daito-Hijiki*, K2: *Hira-Mitsuto*, K3: *De-Mitsuto*, K4: *De-Gumi* (Fig.1 Fig2). The size and shape of the specimens are shown in Fig.3. The columns were cut short(70cm) and fastened to the shaking table, on the assumption that the rocking angle of the column can be ignored. Four columns were placed at the corners of a square plan of 2m by 2m (Fig.4) and the bracket complex placed on the columns. The bracket complex is a combination of 2 elements called '*Masu*' and '*Hijiki*'. These two elements are placed on top of each other connected with wooden dowels as shown in Fig.5. The specimens are full scale model of a bracket complex of a Buddhist temple "*Kitain Jigen-Do*", which is designated as an important cultural property by the national government of Japan.

[1] *Structural Engineering Research Center, Tokyo Institute of Technology, Kanagawa, Japan. e-mail: fujita@serc.titech.ac.jp*
[2] *Dept of Architecture, Grad School of Eng, University of Tokyo, Tokyo, Japan. e-mail: sakamoto@buildcon.t.u-tokyo.ac.jp*
[3] *Dept of Architecture, Grad School of Eng, The University of Tokyo, Tokyo, Japan. e-mail: ohashi@buildcon.t.u-tokyo.ac.jp*
[4] *Institute of Technology, Tokyu Construction, Kanagawa, Japan. e-mail: ms_kimura@hd.tokyu-cnst.co.jp*

TESTING METHOD

Static lateral loading tests and shaking table tests were conducted. A shaking table with 3dimensional movement (Technical Institute of Tokyu Construction Company) was used in the experiment. The response acceleration, velocity and displacement were measured using accellerograms and measuring devices by laser. The movements of the specimens were recorded using 9 video tape recorders. The tests were carried out under 4 conditions (phase). The 4 conditions were a combination of 2 different vertical load and 2 conditions of the specimen (with or without *Biwa-Ita*) as shown in Fig.6. These 4 conditions were named as Phase A, B, C and D. The 2 types of vertical load correspond to the types of roofing. The vertical stress of the columns was calculated on several buildings with different types of roofing and the average was obtained. For the experiment 2 conditions of vertical load was adopted: 2tonf (0.5tonf / 1column) representing thatched roof using bark of cedars and 12tonf (3tonf / 1column) representing clay tile roof. *Biwa-Ita* is the name of a board, which is installed between the beam and the column. The *Biwa-Ita* is about 15mm thick, placed inside a 10mm deep rail cut in the attaching elements (Fig.5). It is ordinarily used in all types of Buddhism and Shintoism architecture, excluding gates.

STATIC LATERAL LOADING TEST

The static lateral loading tests were conducted by fixing the top of the specimen to a steel column standing outside the shaking table, and by operating the shaking table horizontally by sine wave with the period of 40s[1] (Fig.2).

SHAKING TABLE TEST

The schedule of the shaking table excitation is shown in Table1. The excitations were mainly focused on one dimensional excitations (horizontal). But as sliding and rocking were assumed to be two of the main modes, two dimensional excitations (horizontal and vertical) were also conducted for comparison.

The values of the input motions shown in Table1 are as follows.

<u>Random Noise</u>: A band limited white noise X: 0Hz□30Hz, Y,Z: 0Hz□50Hz.

<u>Sine Sweep</u>: Sine wave excitation with constant amplitude of acceleration, and the frequency increasing 0.25Hz for each step. The duration of each step was 5 seconds.

<u>Sine Wave</u>: Sine wave excitation with constant frequency and changing the acceleration from 0 Gal to 200 Gal. The duration of the excitation was 2minutes.

<u>JMA Kobe</u>: The acceleration record measured at the Kobe Meteorological station, during the 1995 Hyogoken-Nanbu Earthquake. This acceleration record was used as the principle input motion.

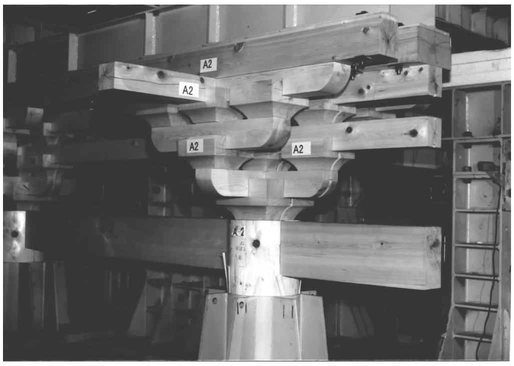


Fig.1 Specimen K4 (*De-Gumi*)

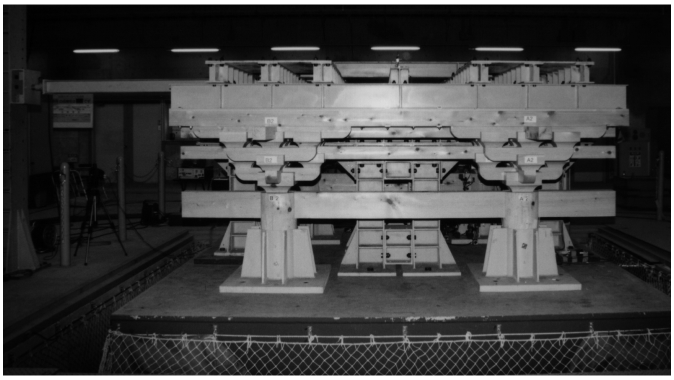


Fig.2 Static Lateral Loading Tests of K4

[1] For specimen K4 the sine wave was 50s/cycle

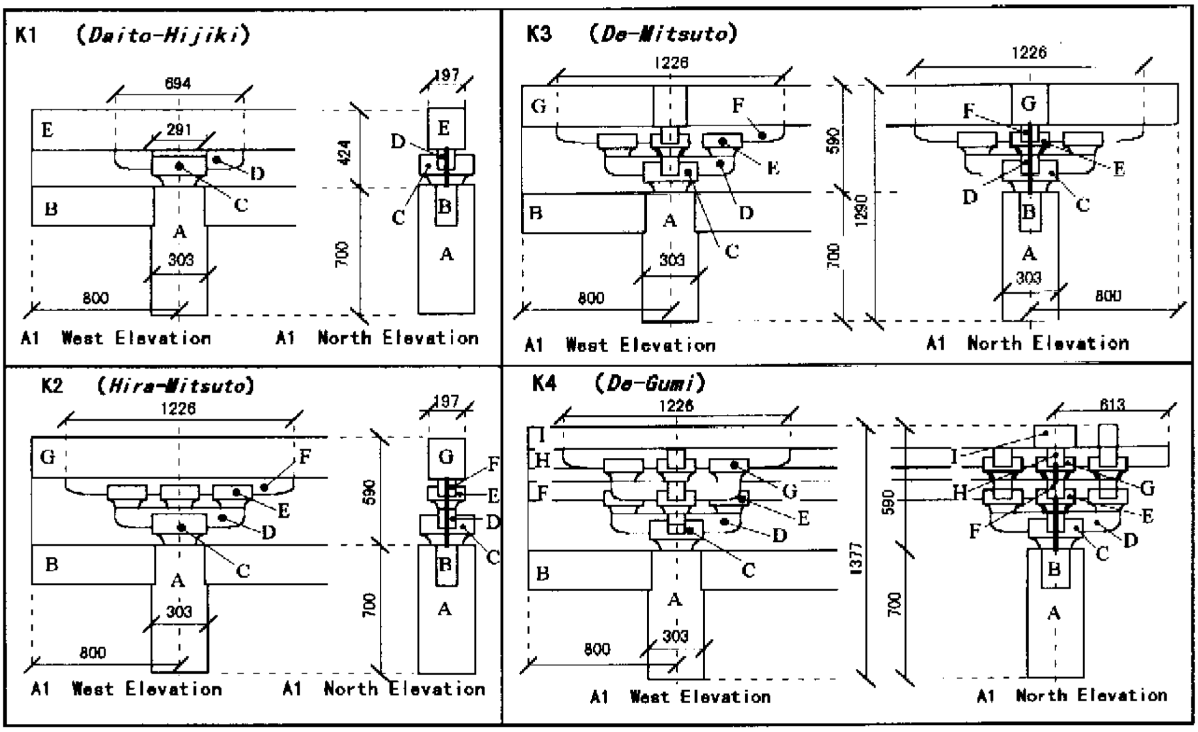


Fig. 3 Elevation and Section of the 4 Specimens (mm)

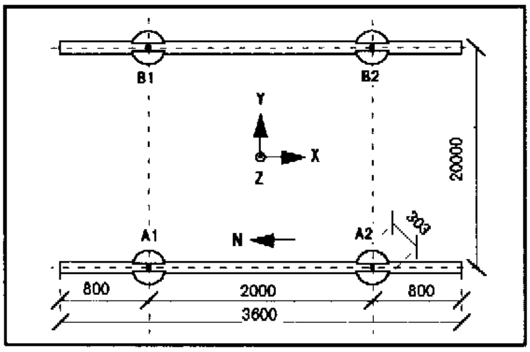


Fig. 4 Plan of the Specimens (mm)

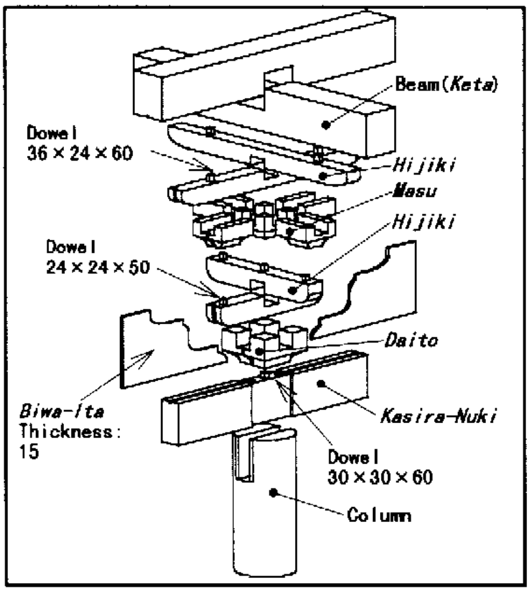


Fig. 5 Example of a Combination and the Names of the Elements (mm)

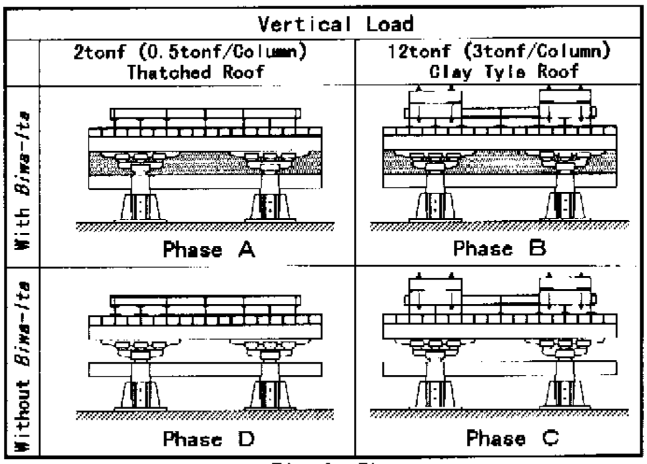


Fig. 6 Phase

Table1 Schedule of Shaking Table Excitation

Input Motion	Dimension	Level		
Micro Tremour	3D-XYZ	-		
Random Noise	1D-X	20Gal	50Gal	-
	1D-Z	20Gal	50Gal	-
	1D-Y	10Gal	20Gal	-
Sine Sweep	1D-X	20Gal	50Gal	-
	1D-Z	20Gal	50Gal	-
	1D-Y	10Gal	20Gal	-
JMA Kobe	1D-X	10kine	25kine	50kine
	2D-XZ	X:10kine	X:25kine	X:50kine
	3D-XYZ	X:10kine	X:25kine	-
Sine Wave	1D-X	(2Hz) 0→200Gal		
	2D-XZ	X:(2Hz) 0→200Gal Z:(7Hz) 50Gal		

RESULTS OF STATIC LATERAL LOADING TESTS

In order to compare the results of the dynamic tests, static lateral loading tests were conducted after the shaking table tests, using the same specimens. The condition of the static lateral loading corresponds with phase D (vertical load: 2tonf, without *Biwa-Ita*). Table2 shows some of the results of the static lateral loading tests. The maximum load and displacement measured in the experiment, the stiffness at 1/400rad, equivalent viscous damping ratio and static friction coefficient of each specimen are shown. The term “relative displacement” indicates the relative deflection angle of the column and the beam as shown in Fig.7. The load was measured by the load cell attached between the steel column and the steel beam connected to the top of the specimen (Fig.2). The equivalent viscous damping ratio was calculated using the equation shown in Fig.7.

Fig.8 shows the load displacement curve of each specimen. Although the shape and combination of the brackets are very complex, the results indicate that the load displacement curve can be idealized by a multi-linear model as shown in Fig.8. The movements of the elements were measured using displacement transducers. The main deformation characteristics for each section are also shown in Fig.8. The 4 different types of brackets showed common characteristics as follows.

- In the region of the initial stiffness, the rotation of *Daito* was the major horizontal deformation element for all the specimens.
- When the horizontal load exceeds the frictional capacity, approximately 1tonf sliding (slipping) between the elements was observed.
- The friction coefficient was approximately 0.5 (1tonf) for all the specimens.
- The location of the sliding was different for each specimen.
- When the horizontal displacement exceeds 0.01rad., the resistance increased again, by another stiffness [5].

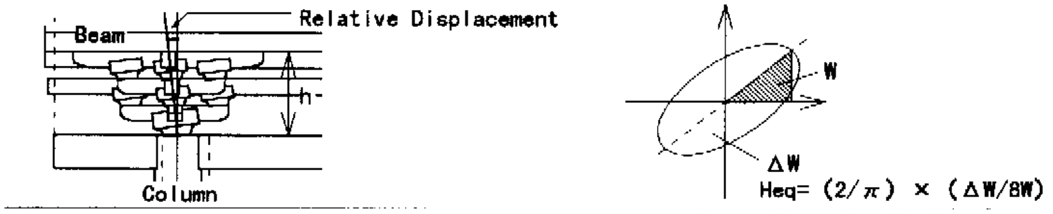


Fig.7 Calculation of Relative Displacement and Viscous Damping Ratio

MODELING

From the results of the static lateral loading tests a non-linear model of the bracket complex is proposed [6], as shown in Fig.9. The deformation procedure of the bracket complex was idealized as follows.

- (O-A) initial stiffness: the *Daito* rotates.
- (A-B) second stiffness: when the horizontal load exceeds the frictional capacity sliding between the elements occur.
- (B) when the horizontal sliding exceeds the gap between the elements, the edge of the dowels meet the edge of the holes.
- (B-C) third stiffness: the *Masu* rotates and the dowels start to deform.

For each section of the multi-linear model the stiffness is determined theoretically from the idealized characteristics of the deformation shown above.

<u>Initial stiffness:</u> Rotation of *Daito*. The first stiffness can be determined by the theoretical stiffness of the elastic deformation of wood perpendicular to the grain of the bottom of *Daito*, assuming that the deformation of the column can be ignored [7]. This stiffness can be determined from the size and shape of the element *Daito*, and the stiffness of the material.
<u>Second stiffness</u>: Sliding between the elements. The stiffness is 0. The resistance can be determined from the friction coefficient of the material. The length of the sliding depends on the construction accuracy, or the surface condition, which is difficult to determine theoretically. In the experiment the sliding was approximately 5mm.
<u>Third stiffness</u>: rotation of *Masu*. The stiffness is determined by the theoretical stiffness of the elastic deformation of wood perpendicular to the grain of all the dowels used in the specimens.
<u>Fourth stiffness</u>: assumed to be the average of the first and third stiffness.
The stiffness of the multi-linear model shown in Fig.8 is the theoretical stiffness shown above.

[5] *This was only seen in specimen K4, as all the other specimens were not tested up to the displacement larger than 0.01rad.*
[6] *This model is a revised version of the non-linear model proposed in [3].*
[7] *The stiffness of the elastic deformation of wood parallel to the grain is approximately 25 times larger than that of perpendicular to the grain.*

Table.2 Results of the Static Lateral Loading Test (Phase D)

Specimen		Max. Load	Max. Relative Displacement	Stiffness (1/400rad.)	Equivalent Viscous Damping Ratio	Static Friction Coefficient
		tonf	rad.	tonf/rad.	%	
K1	*Daito Hijiki*	1.3	0.0031	478	24.1	0.55
K2	*Hira-Mitsuto*	1.3	0.0044	381	79.0	0.59
K3	*De-Mitsuto*	1.1	0.0092	286	26.7	0.51
K4	*De-Gumi*	2.1	0.0300	385	21.4	0.47

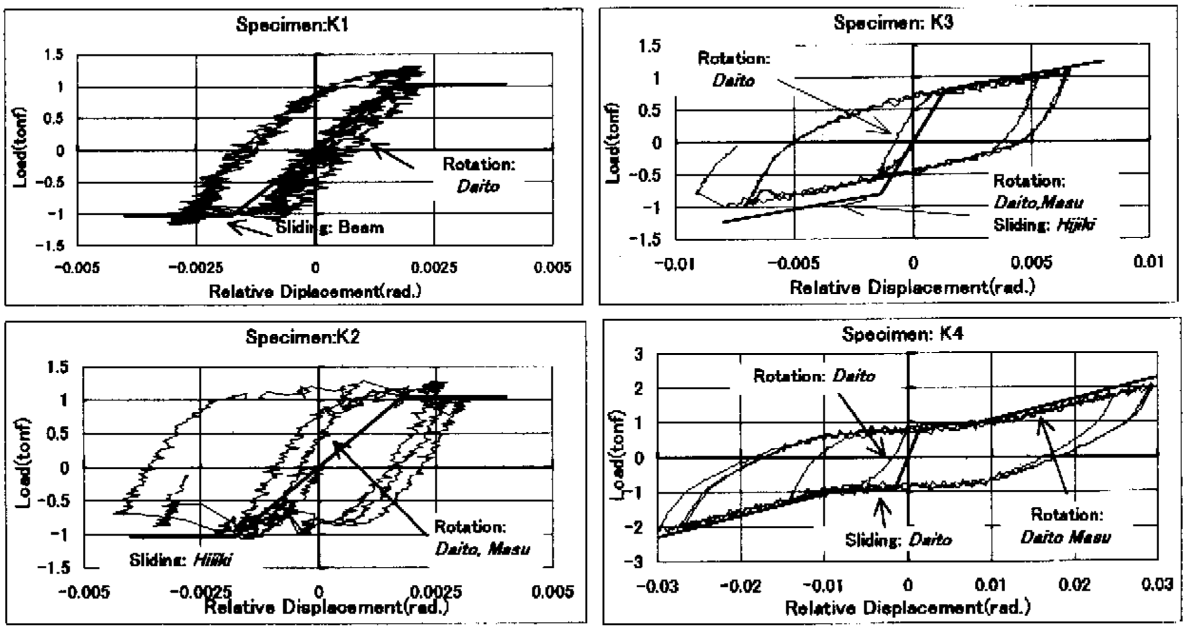


Fig.8 Load Displacement Curve and the Deformation Characteristics

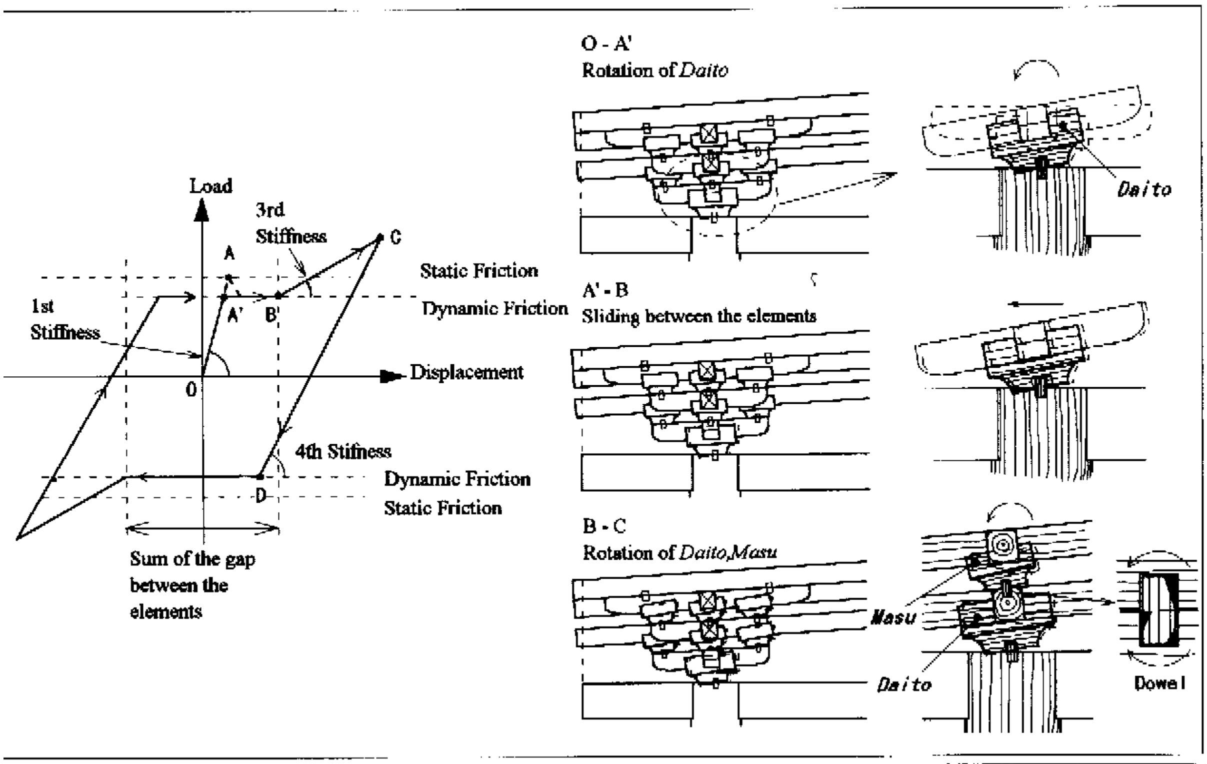


Fig.9 Non-Linear Model B of Bracket Complex

9. RESULTS OF SHAKING TABLE TEST

Table3 shows the natural frequency, damping ratio and the stiffness of the specimens measured by the random noise (maximum acceleration 50Gal) excitation. The damping ratio was calculated from the acceleration response, the stiffness was calculated from the natural frequency and the mass of the specimens. The maximum relative displacement measured in the excitation was approximately 1/3000rad.By comparing the results of phase B with those of C, it is evident that when the *Biwa-Ita* (board) is installed, the stiffness has a tendency to increase approximately 20%. By comparing the results of phase A with those of B, the stiffness of the brackets has a tendency to increase as the vertical load increases. This is a result of the fact that the center of the rotation of the components is unfixed. As the vertical load increases the center of the rotation shifts so that the uplifting of the components decreases. As the theoretical stiffness of the elastic deformation of wood perpendicular to the grain is proportional with the rotation diameter of the elastic deformation, the increase in the stiffness can be theoretically proved by the increase in the vertical load. From the results of the static lateral loading test, the center of the rotation for phase B (0.5tonf/column) was close to the edge of *Daito*, with very small deformation at the bottom, but for phase C (3.0tonf/column) the center of rotation was at the 1/3 of the bottom of the *Daito*. For the different types of the specimens there was no evident tendency in the stiffness.The natural frequency was approximately 5 to 8 Hz for the vertical load of 12tonf, and approximately 15 Hz for 2tonf. The natural frequency of a Buddhist temple of which the size and shape of the specimen was adopted (*Kitain Jigen-Do*: clay tyle roof, 6.4m by 6.4m in plan) was measured by the authors using micro tremor measurements. The natural frequency was approximately 1.5Hz.

Fig.10 shows the load displacement curve of the shaking table test and static lateral loading test. The major horizontal deformation characteristics are also shown in the figure. The horizontal axis shows the relative displacement, the vertical axis represents the base shear coefficient of the specimens. The base shear coefficient was used, because the vertical load of the static lateral loading test was 0.5tonf/column, and that of the shaking table test was 3tonf/column. From the figure the shape of the load displacement curve and the deformation characteristics of both static and dynamic tests are fairly close. Thus the application of the model proposed from the static lateral loading test seems appropriate.

10. APPLICATION OF THE MODEL TO EARTHQUAKE RESPONSE ANALYSIS

Non-linear earthquake response analyses of the bracket complex was carried out using the proposed model. The specimen was idealized by a one mass shear model. The Newmark β method was used. Fig.11 shows one example (specimen K4) of the response analysis. The load displacement curve, time history of the relative displacement and time history of the shear force are shown. The results of the response analysis are compared with the results of the shaking table test. The input motions were both JMA Kobe NS maximum velocity: 50kine. The parameters used in the model were determined from the results of the shaking table tests.

The results of the analyses shows fairly good agreement with those of the shaking table test until 17s, but after 17s the value of the relative displacement becomes smaller than the results of the experiment. This is because the movement of the bracket complex is dependant on the frictional capacity of the specimen, and the relative displacement could increase largely once the shear force reaches a certain value (frictional capacity). Thus the amplitude does not differ very greatly. Although the parameters used in the model needs further consideration the model itself seems appropriate in idealizing the bracket complex.

11. SIMULATED EFFECT OF THE BRACKET COMPLEX ON THE WHOLE STRUCTURE

Fig.12 shows an example of the non-linear earthquake response analysis of the combination of 2types of traditional walls (mud wall, frame) and bracket complex. The traditional walls were idealized by a bilinear+slip model, from the results of the shaking table test carried out by the authors [3]. The result of the analyses shows that for the combination of the frame and the bracket, the maximum relative deflection angle of the bracket is approximately 1/60 of that of the frame, and the story drift of the frame does not differ greatly with or without the brackets. But for the combination of the mud wall and the bracket, the story drift of the bracket is approximately 1/2 of that of the mud wall, and the amplitude of the story drift of the mud wall is smaller when the bracket is set on the wall. This result suggests that when the stiffness of the wall and that of the bracket complex are close to each other, the story drift of the wall has a tendency to decrease when there are brackets set on top of the wall. But when the stiffness of the wall is much smaller compared with that of the brackets, as in the case of the frame, the brackets do not deform so much and act as a rigid body.

Table3 Results of the Shaking Table Test (Random Noise 50Gal Excitation)

Specimen	Phase	Biwa-Ita	Vertical Load	Natural Frequency	Damping Factor	Stiffness
			tonf	Hz	“	tonf/rad.
K1	A	›	2	17.7	7.0	3012
	B	›	12	8.3	11.1	3777
	C			12	7.0	15.5	2698
K2	A	›	2	15.2	5.2	2528
	B	›	12	7.3	11.0	3354
	C			12	6.4	9.3	2580
K3	A	›	2	13.9	11.4	2270
	B	›	12	6.9	12.8	3044
	C			12	5.5	9.3	1909
K4	B	›	12	8.0	8.5	4032
	C			12	5.8	6.8	2083

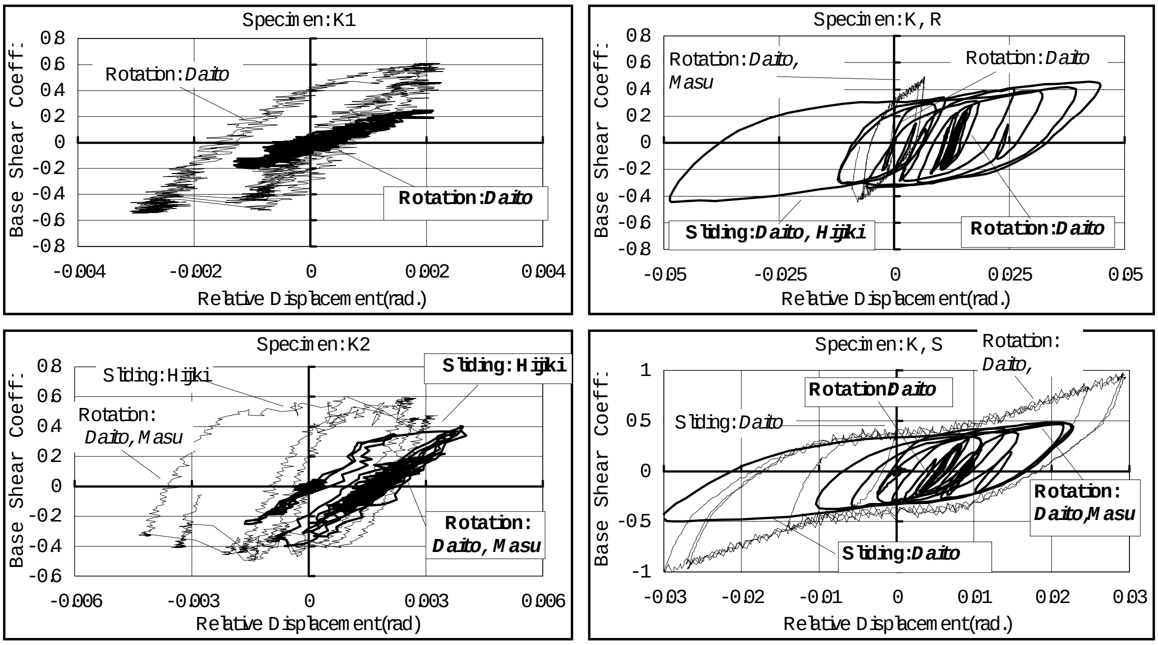
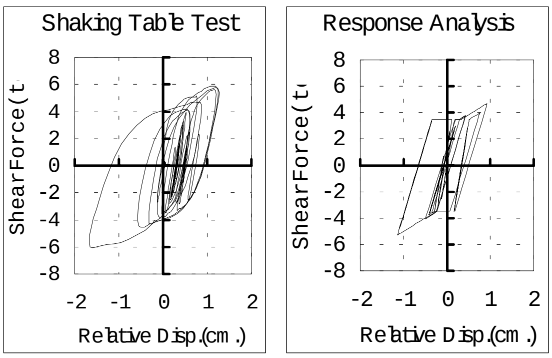
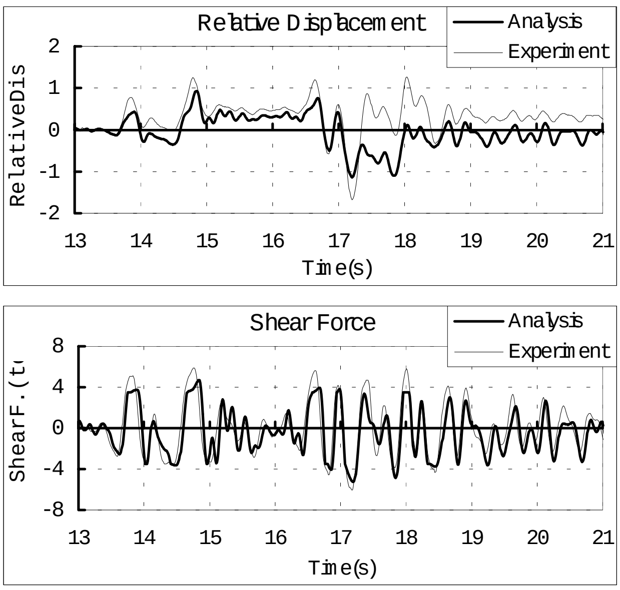


Fig.10 Load Displacement Curve and Deformation Characteristics (Comparison of Static and Dynamic Tests)





Parameters	
Input Motion	JMA Kobe NS(50kine)
First Stiffness (tonf/cm)	20
Third Stiffness (tonf/cm)	2
Friction (tonf)	3.5
Weight (tonf)	12
Damping Factor (%)	10

Fig.11 Results of Earthquake Response Analysis

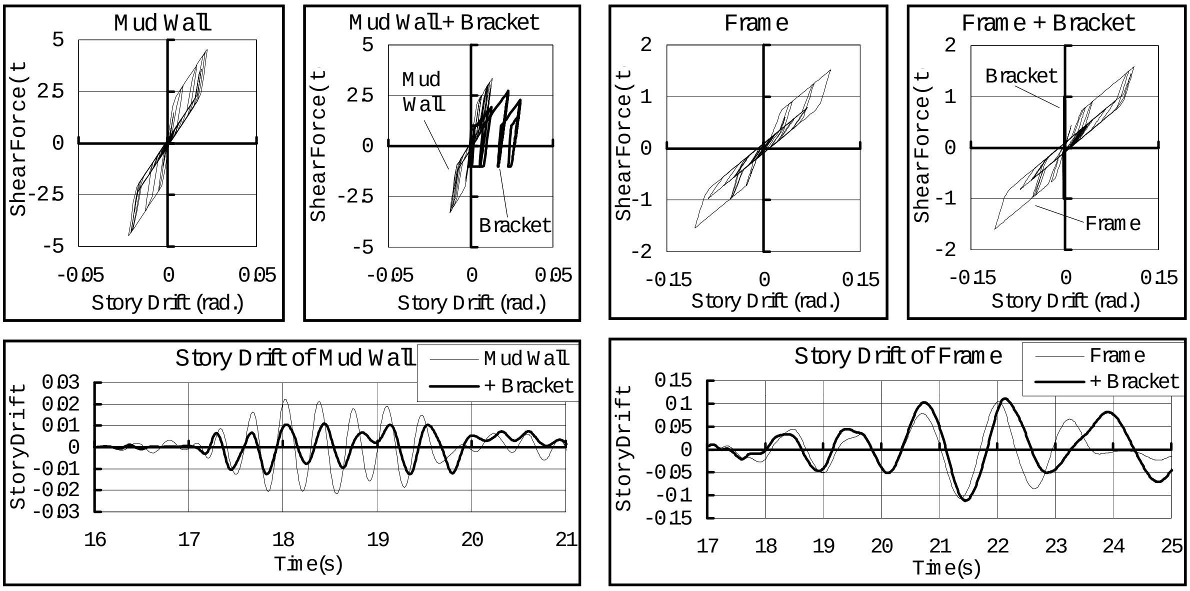


Fig.12 Earthquake Response Analysis of Wall and Bracket Complex Combination

12. CONCLUSION

From the results of the static lateral loading tests a non-linear model of the bracket complex was proposed. Non-linear earthquake response analyses were carried out using the proposed model, and the results were compared with those of the shaking table tests. It was proved that although the parameters need further consideration, the model itself seems fairly appropriate in idealizing bracket complex used in traditional timber structures. By carrying out non-linear earthquake response analyses on the combination of walls and bracket complexes, it was proved that the bracket complex has a tendency to decrease the relative deflection angle of structures if the stiffness of the walls are close to that of the bracket complexes.

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