Preservation and Seismic Retrofit of the Traditional Wooden Buildings in Japan

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The structural system of Japanese traditional buildings is focused as a typical case of ‘temporal design’ in the architectural field. A series of the studies aims to evaluate the dynamic performance of the traditional wooden structure as well as that of each resisting part. Vibration tests of a full-scale model subject to strong ground motion were carried out on the shaking table. Also, in this paper is shown an analytical method for seismic evaluation as the earthquake response analysis, which clarify the seismic characteristics of the traditional wooden structure quantitatively. On the basis of dynamic performance, which is characterized by stiffness, ductility and damping capacity, the author shows the seismic safety criteria and makes a proposal for the preservation and seismic retrofit of the traditional wooden buildings. Regarding the wooden structure, columns or beams are not jointed rigidly, unlike those of the reinforced concrete or steel structures, which triggers great deformation at joints during the earthquake. Focusing the connecting part, viscous dampers are installed in the wooden frames to increase the original damping capacity as useful device for the retrofit works. In this respect, this paper presents the upgrade effects on the cultural property buildings.

Keywords: traditional wooden buildings, seismic characteristics, analytical evaluation, damping capacity, viscous damper

1. INTRODUCTION

The structural system of Japanese traditional buildings is a unique wooden framework. The traditional buildings, which appear mainly in the old residential or religious ones as shown in Figs.1(a), (b), and (c), reflect their climatic conditions and the historical backgrounds in the region. Japanese culture would be considered to originate from wooden culture, because residing and religion are the basic scheme of human life. Many people admire old temples, old shrines and traditional detached residences as “Japanese architecture is refined, elegant, delicate ...” [1,2]. In Japan, however, the climate conditions are severe as strong sunshine in summer, heavy rain in June and July, strong wind of ‘Typhoon’ and also sudden earthquakes. Traditional wooden buildings have withstood those severe conditions for a long time with the help of many technological improvements.

Framework system of the Japanese wooden buildings has completed in the middle age, 11-13th century [3]. After that, Japanese carpenters have continued to employ the system without having big changes until pre-modern age, early 20th. Japanese traditional structure has owed to the experiences and the perceptions of old carpenters, not by the rational theories. Technological changes in the Japanese wooden buildings are shown as following transition in the architectural history;

Ancient age;	Piling up horizontal beam with *To-kyou* on the vertical column.
Middle age;	Using *Nuki* for horizontal beam to obtain some stiffness and damping.
Pre-modern age;	Adding to stiffness with wooden braces or sand walls.
Modern age;	Simplifying the connection details by using metal fittings.

(‘*To-kyou*’ and ‘*Nuki*’ are the specific Japanese structural elements to be explained later.)

Braces often cause the wooden frameworks to warp in time duration. Detail simplification, which is caused by reduction of the skilled carpenters and unreasonable imports of western techniques, is rather inevitable in modern times, but it may lead the Japanese buildings to lose the national tradition. The changes after 19th century make nothing of structural flexibility and toughness. Nowadays, structural preservation of most cultural property buildings means to keep the structural system to the state of the middle age. In this connection, this paper treats the framework of the middle age as Japanese traditional structure. In fact, some half of Japanese modern residences is still constructed by similar framework in old towns as Kyoto, Nara, Kanazawa and others [4].

(a) Shrine in Matsue

(b) Temple in Kyoto

(c) Detached houses in Kanazawa

Fig. 1. Japanese traditional buildings.

Why has this framework continued so long? The reason would lie in the characteristics of wooden material. Wooden members are reusable even after changing their forms. As far as natural forests exist, wooden materials are recyclable for building construction. Among cultural properties in Japan, there exist no wooden buildings which have not be changed structurally. Temples and shrines, which sustain their structural system for 1,000 years, have been transformed in a period of some decades (roof tiles or interiors) or some centuries (structural frameworks). Even when burnt down, they have been rebuilt in the original forms with slight improvements. Cultural property buildings in Japan have completed in such ways. We, living in modern times, have to learn the notion of 'sustainability' from those facts. But structural properties of the traditional wooden buildings have not yet been clarified by modern theories. It is very surprising and mysterious that traditional forms continue for millennium by carpenters' experiences and perceptions.

Over 5,000 human lives have been lost by collapse of wooden residences in 1995 Hyogo-ken Nanbu Earthquake. However, wooden residences are being rebuilt in same sites and many people continue to live in detached wooden houses. The earthquake must be a severe experiment for our wooden culture. We have to solve the mystery of the traditional wooden structure by our modern technologies for the sustainable Japanese lives and culture.

2. STRUCTURAL ELEMENTS OF THE FRAMEWORK

In 1999, new research activities have started by the special committee within Architectural Institute of Japan 'Restructuring of the wooden structure and wooden culture' headed by Prof. Yoshiyuki Suzuki (Kyoto University). One of these activities (Working Group 1) aims to evaluate seismic performance of the whole building as well as each structural element through vibration tests on the full-scale model, and to pursue the experimental result analytically in order to obtain the vibration characteristics of the traditional wooden framework quantitatively. Traditional structural system of Japan has specific resisting mechanism differentiated from the rigid joint frame such as steel structures or reinforced concrete structures.

The author has been involved in WG1 and has studied the related past researches [5-9]. Japanese traditional wooden structure consists of simple frames, which contains only vertical and horizontal members but no diagonal members or no rigid walls. Connecting parts of members have unique details peculiar to wooden materials. Such structure requires proper weight for its stable state under vertical and lateral loads. While several researches have been performed on the traditional wooden structure in the past, unfortunately, they have treated only single element and static behavior of the structure. Natural material as wood has uneven quality in strength and changes the quality with time duration. So mechanical properties of wooden material is very difficult in quantitative verification. Nevertheless, wholly understanding of structural characteristic and dynamic performance is the key to solve the mystery of these structures.

According to the past researches, following components are referred as structural elements of the traditional wooden buildings (see Fig.2) :

(1) '*To-Kyou*' (assembled brackets standing between the upper *Nuki* and the girder which supports heavy eaves and roof at the top of column) ;

To-Kyou consists of the rectangular layers of brackets and blocks which overlap each other with dowels. When *To-Kyou* has a vibration, partial compressive strain is caused between each component, and obtains proper stiffness and damping characteristics as an assembled system.

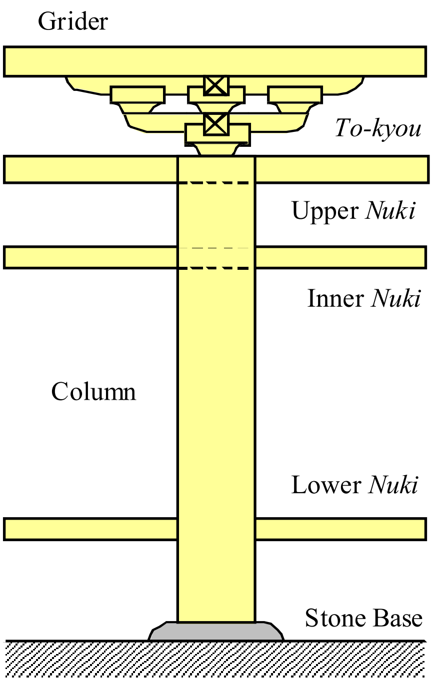

Fig. 2. Structural Flements.

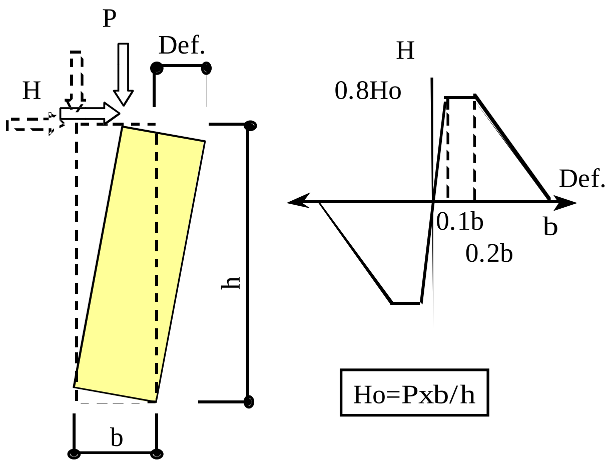

Fig. 3 Restorable-inclination.

Fig. 4. Static test on *Nuki*

(2) '*Nuki*' (main horizontal tie beam which penetrate columns) ;

In column-*Nuki* joint, when having a continuous bending, partial compressive strain is caused between the top/bottom edges of *Nuki* and column body, and finally *Nuki* becomes a structural element which possesses stiffness and damping characteristics.

(3) 'Restorable-Inclination';

When a column inclines like a rigid body, heavy weight of the roof works on the column through horizontal girder and *To-Kyou*, and then restoring force occurs in response to the inclined angle as Fig.3. However, when the degree of inclination exceeds certain limit amount, it starts to work to further the inclination as *P-delta* effect [5].

(4) 'Column-Base';

A Column is not fixed at the bottom but only placed on the stone base, and therefore it works against excessive input, i.e. it reduces the excessive input by rocking or sliding as the base-isolation system.

Assembling the structural elements shown above leads to the flexible and tough frame. This frame would have some stiffness and proper damping in spite of low capacity.

In the traditional framework, rectangular frame subject to seismic force deforms in parallelogram as well as column's rigid-like rotation. In this performance the work of horizontal member *Nuki* is very important. The seismic capacity of the frame would be determined by the sum of *Nuki*'s capacity and column's restorable-inclination force. According to the past researches, *Nuki*'s capacity is obtained by compressive strain characteristics of wood material at the column-connecting part [5,7], when *Nuki* is tightly fixed to column with hard wooden wedges. This unique traditional element '*Nuki*' was first employed in '*Nan-dai-mon*' (South Gate) of the *Todaiji-temple* by a Buddhist *Cho-gen* (1199AD). *Nuki* is the suitable method for wooden structure because wood is convenient material to be manufactured by hands, and has been the main structural element in the wooden buildings of all kinds in Japan since the middle age.

Currently, the author has performed static and dynamic tests (Fig.4) on the actual size *Nuki*, which are simply interlocked ("*Ryaku-Kama joint*") in the column bodies. Fig.5 shows the test result on the interlock jointed *Nuki* compared to the continuous one. In this result, we recognize that *Nuki* of any case is never broken until the deformation angle of 1/15 radian. Certainly, *Nuki* has high ductility and some damping capacity in spite of low strength and low stiffness.

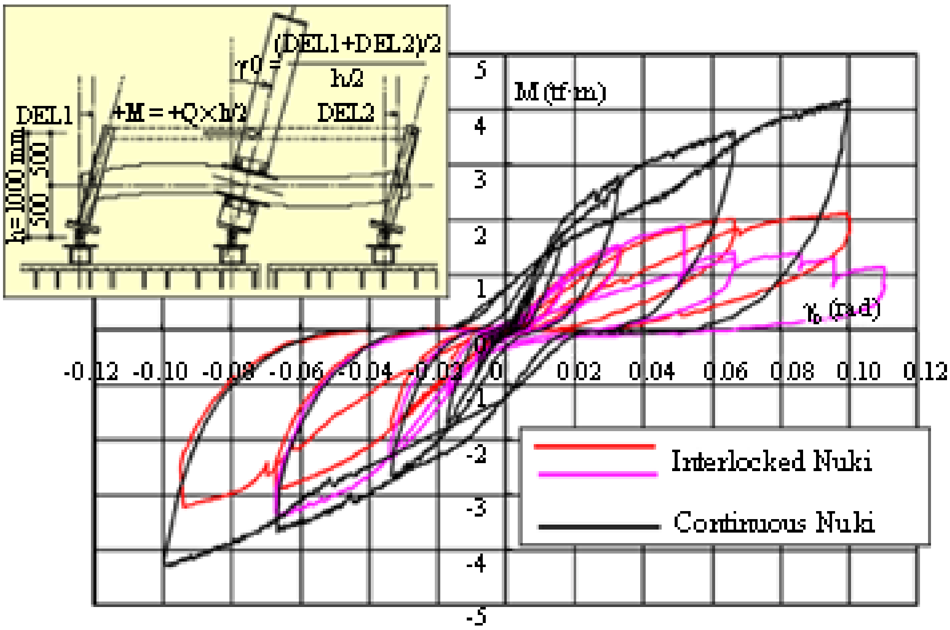

Fig. 5. Test results of interlocked Nuki and continuous Nuki

Fig. 6. Vibration test on full-scale model.

3. SEISMIC PERFORMANCE AND SAFETY CRITERIA

Considering the seismic elements described in Chapter 2, the author has performed dynamic analysis on the whole structure of a typical old temple, which was rebuilt in the middle age. (See the detail of analytical method at Chapter 4.) As the result of this analysis, the structural system withstands the strong ground motion at 40 cm/sec (maximum velocity level) with a large deformation response up to the inter-story angle of 1/30 radian. Also WG1 of Special Committee in AIJ has obtained similar result in the vibration test on the full-scale model as shown in Fig.6 [10].

As the results of this experiment, the following matters are focused:

(1) The hysteresis loop is stable spindle-shape at the natural period of 1.5-2.0 seconds.

(2) The maximum deformation reaches to 1/30 radian in story drift angle. In spite of the large deformation, it returns to the original position like an elastic body after shaking.

(3) The viscous damping ratio (heq) is some 10% as the whole structure.

The whole vibration system is influenced through the effective work of damping capacity by *To-Kyou*, compressive strain effect of *Nuki*, hysteresis characteristics of inclined column (restorable-inclination) and sliding performance of column-base, all of which are characteristics of the traditional wooden framework, and result in making the whole building

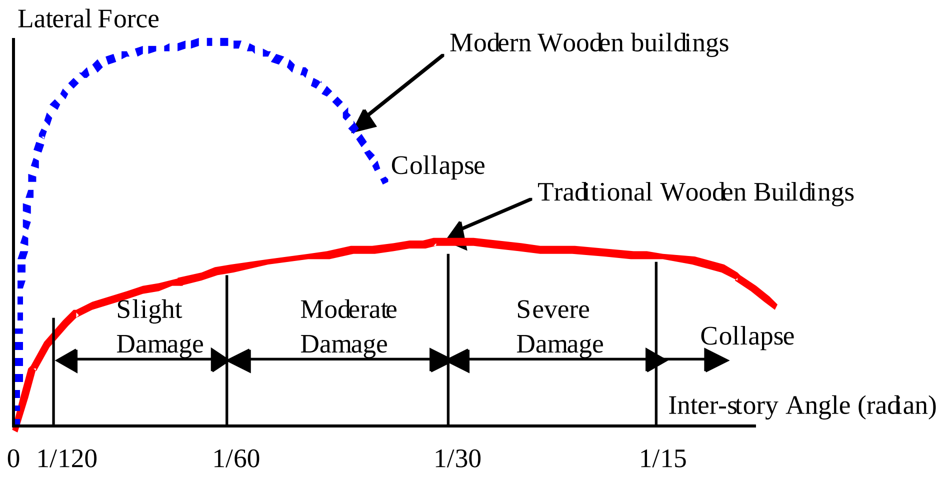

Fig. 7. Deformation characteristics of wooden buildings.

to possess damping capacity up to 10% or so. But we must pay attention to the fact this toughness in the experimental results was obtained by fresh materials of specimen. Irregularities of materials and handmade process provide low precision in all connecting parts, a degree of which would increase with time duration. High humid condition also leads natural material as wood to decay easily. Japanese traditional wooden buildings existing today, therefore, are not considered to have higher performance than their original states. The technical point leading to the seismic safety has to be separated in two ways: first, structural problem, and second, material problem. This paper treats the first way, that is, traditional buildings are in the original state of wood materials. Consequently, decayed wood materials must be repaired before or at the same time of seismic retrofit.

On the assumption that wood materials are fresh, we can make the seismic safety criteria of the traditional wooden buildings as follows, which are obtained from the past experimental researches and several own studies in relation to response deformations of inter-story angle (R) :

(1) $R < 1/120$; Almost elastic, no damage.
(2) $R = 1/120-1/60$; Slight damage, reusable with slight repair.
(3) $R = 1/60-1/30$; Moderate damage, available to reuse with sizeable repair.
(4) $R = 1/30-1/15$; Severe damage but not collapse, indispensable of seismic retrofit after repair or necessity of rebuilding.
(5) $R > 1/15$; Collapse (or to be considered).

Figure7 shows the generalized relationship between the lateral force and the deformation of the old residential houses compared to the modern wooden houses constructed according to the present Japanese building codes. Seismic elements of the old residential houses are characterized by Nuki or sand wall, not rigid brace and panel as in modern houses. Here, wecan notice that modern standards or specification of wooden structure are not useful in judging seismic safety and in planning preservation of the traditional buildings. The traditional wooden buildings require us to use specific technical methods for preservation and seismic retrofit. In fact, there are many existing buildings of traditional wooden structure, most of which have less yielding capacities than 0.1W (W = weight of the building) and predicted inter-story angle for great earthquakes (maximum ground velocity = 40-50cm/sec) are over 1/15 radian. Therefore the reasonable technique is strongly needed for their seismic retrofit.

4. NUMERICAL EVALUATION

Modern engineers can verify the seismic safety of building structure by earthquake response analysis as the usual method, while the conventional method for the wooden building only has been the static analysis. Japanese building code after mid 20th recommends the simplified calculation using ‘wall quantity’ for the structural design and seismic evaluation. But the dynamic analysis should be the very effective method in evaluating traditional wooden structure from the viewpoint of the structural characteristics. However, it is needed that the basic data of structural elements are completed and reliability for analytical results increases. At present, practical way is to choose an appropriate method according to the classification of wooden buildings as indicated in Fig.8. In this paper the author introduces the 3-D precise analysis using EWS system [11].

Analysis is undertaken using MSC-NASTRAN which employs equivalent linear analysis method, and restoring force

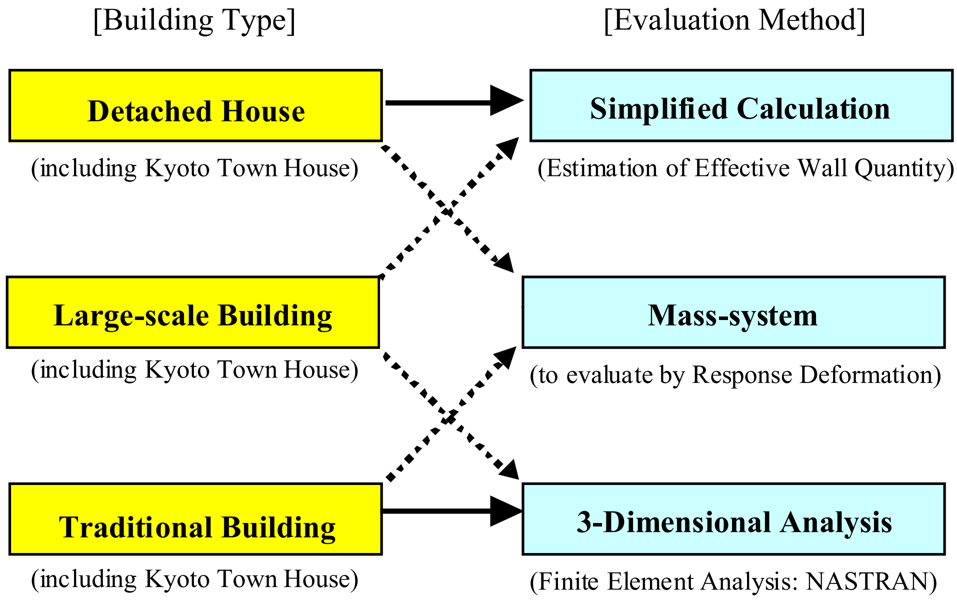

Fig. 8. Analytical model for structural elements.

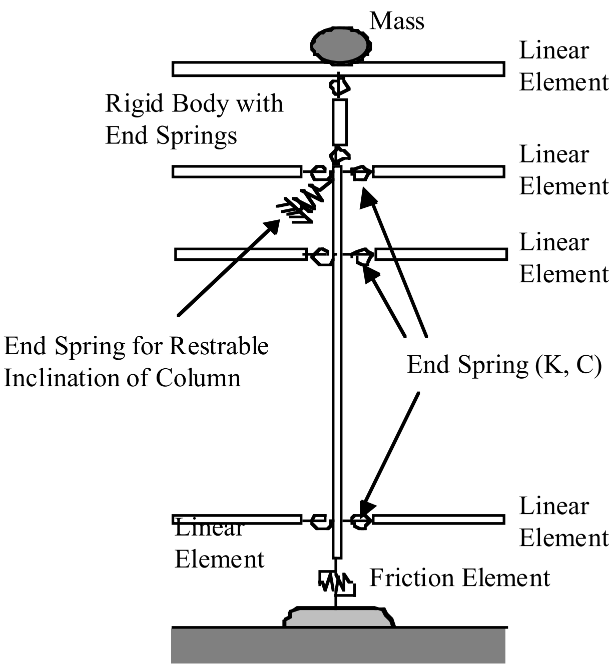

Fig. 9. 3-D analytical model for actual temple.

characteristics or damping characteristics are set up in respect of each element as shown in Fig.9. For the analysis, models are established on four structural characteristics of the traditional wooden structure mentioned in Chapter 2. For each element, numerical values for its analytical model are obtained from the past experimental researches. To define equivalent stiffness, the inter-story angle is supposed to be 1/30 radian in these references. In our dynamic analysis, heq = 2% is speculated as internal viscous damping ratio which the material itself has.

Figure10 shows the 3-D analytical model for the actual traditional temple tions; besides deformation response reaches to 1/17 by maximum inter-story angle under the ground motion level of 50cm/sec velocity earthquake. This result predicts the temple to be greatly damaged or to collapse and to require sizeable upgrade in the seismic performance. When adding wooden-walls in several frames and employing 150 of connecting-type visco-elastic dampers (mentioned in the next chapter), we can estimate the response deformation to reduce 50%, that is, moderate damage, never collapsing. Earthquake response analysis is very useful to obtain quantitative results and to make a concrete plan for the seismic retrofit.

Reliability on the earthquake response analysis has been obtained by the vibration test using full-scale model. Figure11 shows the comparison between analytical result and experimental one regarding the response deformation and acceleration. The earthquake wave adopted is JMA Kobe NS wave (scaled at max. 300cm/s^2). The analytical results almost successfully track the results of experiment. This linear method is capable of precisely figure out some important factors such as maximum deformation without setting up hysteresis characteristics of each structural element. But analysis is based on the assumption that all members are fresh wooden materials. We should grasp the analytical results with some allowance.

5. TECHNICAL METHODS FOR SEISMIC RETROFIT

Conventional methods for seismic retrofit have been increasing stiffness and strength of frames or members by using steel members even in the traditional wooden buildings from Meiji-

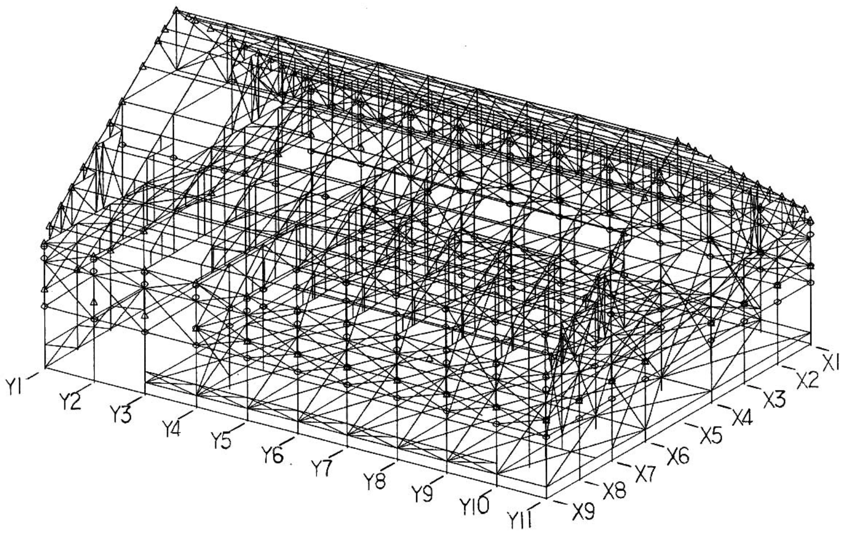

Fig. 10. 3-D analytical model for actual temple.

period to date, while 'Preservation Law of Old Temple and Shrine' was established in 1897. But it is after 1995 Hyogo-ken Nanbu Earthquake that the seismic retrofit of traditional building has become popular in Japan. In this situation, Ministry of Culture has set the guideline for seismic evaluation and retrofit for cultural property buildings in 2000 [12]. That guideline requires 'technical authenticity' for retrofit works. Technical authenticity means to avoid employing the structural system changing original characteristics and also to avoid adding members or frames which cannot be easily removed. It seems to be very difficult for modern engineers who have been accustomed to conventional modern buildings to accept the guideline's demand.

Recently many vibration control methods have been employed in seismic retrofit works of various buildings. We are forced to evaluate the seismic capacity of traditional buildings with sizeable error considering irregularity in material properties and quality change of woods. However, we can estimate the seismic performance of high-tech modern devices with reasonable accuracy because of being produced under the stable quality control. The author is proposing the basic concept for seismic retrofit as 'increasing viscous damping capacity with holding limited strength and wide deformation range.' Here, the limited strength means yielding capacity of the frame of [0.1] x [weight of frame] or more, and the wide deformation range means lateral deformation performance up to inter-story angle of some 1/15 radian. The deformation performance in the wooden structure would be obtained from the ductility of connecting parts, which is not tightly fixed. As the better way for seismic retrofit of the weak traditional wooden buildings, we should strengthen the frame using wooden members and employ viscous damping devices [13]. For the traditional wooden structure, connecting part of the column and *Nuki* is not rigidly jointed, which causes great rotation in earthquake. Great rotation causes great deformation of the frame, up to collapse. This leads to a notion that connecting-type damper is effective to increase the internal viscous damping of the building as well as to improve the seismic performance (see Fig.12).

This idea was tested using full-scale model on the shaking table [10]. The damper consists of three sheets of triangular stainless steel (SUS304, 300 x 300mm x 5mm thick) between each of which two layers of visco-elastic material (acryl, 5mm thick) are inserted. Each steel plate is tightly connected to column or *Nuki* respectively. The visco-elastic material deforms in response to rotating deformation of connecting part, and absorbs wave energy. In this experiment, four dampers were placed at column-lower *Nuki* connections in each direction (Fig.13). The results of the experiment are successful, where the viscous damping ratio increases 5% (to 15%) and the maximum deformation reduces 25% by employing the visco-elastic dampers. Fig.14 shows hysteresis curves of both cases, with and without dampers. In the traditional wooden frame, this device placed at lower *Nuki* would show similar effect being placed at upper *Nuki* or inner *Nuki* because of column's rotating as rigid body.

Viscous damping device behaves in velocity-dependent performance and has small stiffness. Those characteristics never lead the employed frame to disadvantageous side. If the device is slight one, handling, installation and removing are very easy. Such device is suitable for seismic retrofit of the cultural property buildings. Connecting-type dampers de-

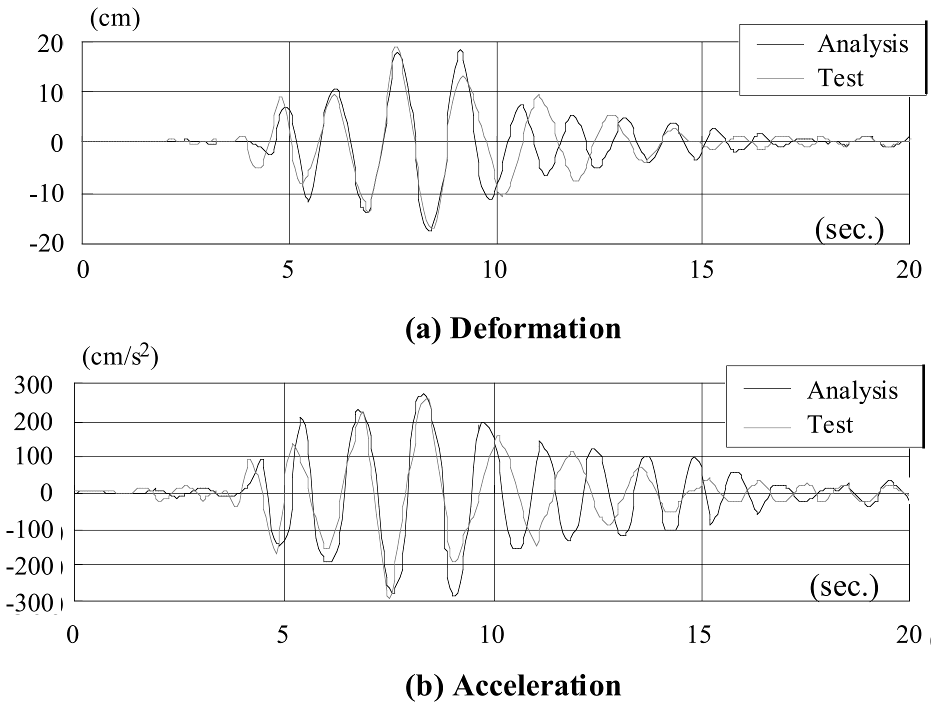

Fig. 11. Analyzed time-history response with test result (JMA Kobe NS 300 cm/s²).

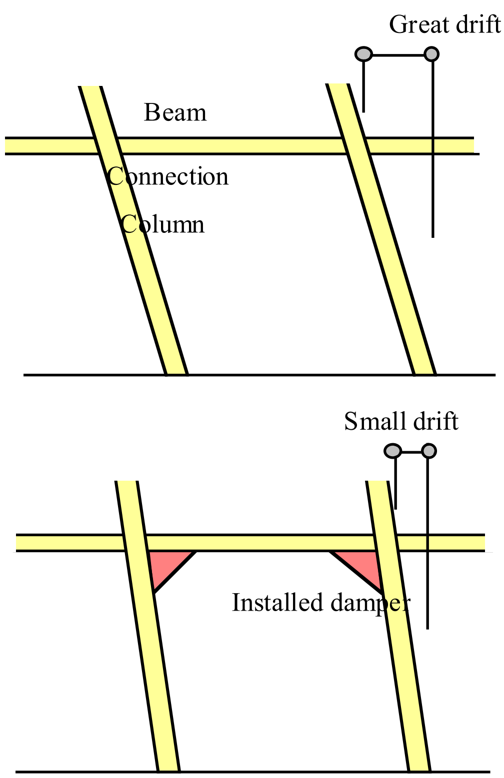

Fig. 12. Image of the seismic retrofit using Visco-elastic dampers.

scribed above are 10kg in each weight and are installed by using specific fittings. In the case of detached house, column size of which is small as 10-12cm width, we should use slighter damper of 15cm type. It is 1kg in weight and is installed directly in the wooden connection by screws. Connecting-type visco-elastic damper is one of the solutions for seismic retrofit of Japanese traditional buildings.

6. CONCLUDING REMARKS

The structural system of the traditional wooden buildings in Japan is unique, which has completed in the middle age as holding proper stiffness and damping capacity, and to date, the system has improved slightly to sustain Japanese wooden culture. It can be said that the temporal design has been accomplished in the field of traditional wooden buildings. But recent 50 years, modern technology has not yet been properly applied. This paper presents the structural system of Japanese traditional buildings on the basic performance of wooden frameworks.

The structural system is consists of 3 elements; '*To-kyou*', '*Nuki*', and 'Column-Base' characterize the flexible performance when subject to strong ground motion. The whole vibration system is influenced through the effective work of damping capacity by *To-Kyou*, compressive strain effect of *Nuki*, hysteresis characteristics of restorable inclination of column and slide of Column-Base, all of which are characteristics of traditional wooden structure, and result in making the whole building to possess damping capacity up to 10% or so. But the seismic safety can be obtained under the balanced capture of stiffness, strength, ductility and damping capacity. Seismic safety criteria are proposed according to the damage

Fig. 13. Installed damper at lower Nuki.

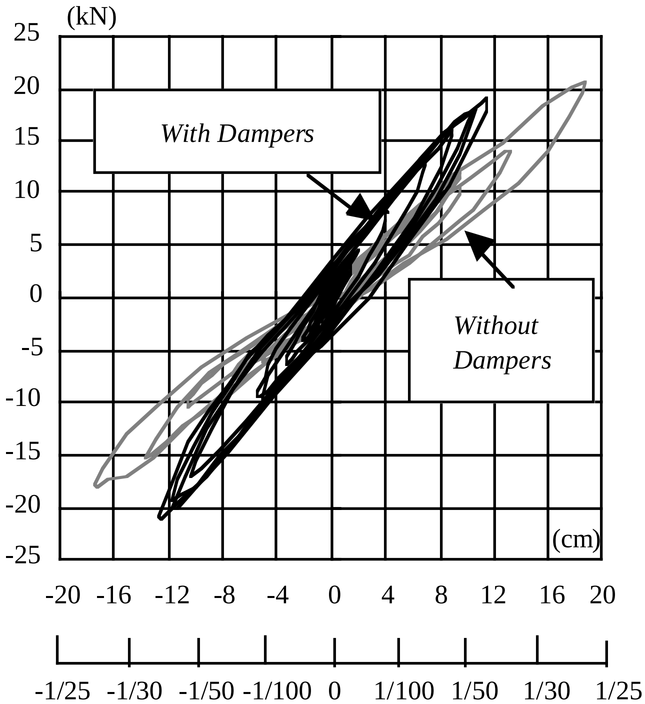

Fig. 14. Tested hysteresis curve (JMA Kobe NS 300 cm/s^2)

grades with reference to the past researches and the full-scale model tests. The extreme state in the traditional wooden structure is defined as the inter-story angle of 1/15 radian. There are many traditional buildings which are predicted to have great damage or collapse.

Also, when structural characteristics are made into the model as regards equivalent linear rigidity and equivalent damping, some important factors such as maximum deformation can be precisely output. Earthquake response analysis is very useful to obtain quantitative results and to make a concrete plan for the seismic retrofit.

For the seismic upgrade of such traditional wooden frames, connecting-type visco-elastic dampers have been verified to increase damping capacity without loosing the flexibility of the structure. Employing the dampers is better method to maintain 'technical authenticity' of the cultural property buildings because they never change the essential characteristics.

Through a series of studies, we have obtained a useful technique for evaluating, planning and accomplishing the preservation and seismic retrofit of the traditional wooden buildings in Japan.

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