13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 666

ENERGY-BASED EVALUATION METHOD OF SEISMIC PERFORMANCE OF TIMBER STRUCTURES

Nobuyoshi YAMAGUCHI[1] and Chikahiro MINOWA[2]

SUMMARY

For the purpose to evaluate seismic performance of timber structures against severe earthquakes like as 1995 Kobe earthquake, it is desired to propose survivability limit state criteria and design method for them. Shaking table test of timber structures using JMA Kobe motion was conducted, and collapse of timber structures was simulated physically on the shaking table. Load-deformation curves considering P-delta effects and non-linear damping factors were obtained. Dynamic yields and asymmetrical features were observed in them. Basic asymmetrical hysteresis model for timber structures was proposed. Energy-based evaluation method using capacity of energy absorption was applied to the test results. Process of energy absorption and distribution in the equation was analyzed. Relationship between capacities of energy absorption and collapse of structures was clarified. Energy-based design using Housner's assumption was verified in shaking table tests. Capacity of asymmetrical hysteresis model is proposed for survivability limit state criteria. Application of energy-based design for survivability limit state criteria is discussed.

INTRODUCTION

Ultimate strengths design methods evaluates both of ultimate strengths and ductility of structures. This is equivalent to evaluate energies, because energies are the product of forces and displacements. Sum of kinematic and input energy of masses balances to the sum of absorbed energies in viscous-damping and elasto-plastic response of structures. These concepts were used for earthquake-resistant design method based on energy balance that had been proposed by Akiyama [1]. After 1995 Kobe earthquake, a series of shaking table tests using shear walls was conducted in NIED from 1997 to 2000 by Yamaguchi and Minowa [2]. Shear walls of Japanese conventional post & beam structures were tested. For the purpose to evaluate seismic performance of timber structures using energies, energy-based evaluation method was applied for results of these shaking table tests.

[1] Building Research Institute, Tsukuba, Japan, Email:yamaguch@kenken.go.jp [2] National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Japan

ENERGY-BASED EVALUATION METHOD

Equation of Vibration Considering P-Delta Effects

Equation of vibration considering P-delta effect is introduced in equation-1. m, c, k and L is masses, viscous-damping coefficient, stiffness and height of masses, respectively. $\ddot{x}$, $\dot{x}$, x and $\ddot{y}$ is relative response accelerations, velocities, displacements and input accelerations for shaking table .

$$m\ddot{x} + c\dot{x} + kx - mg\,\frac{x}{L} = -m\ddot{y} \tag{1}$$

Cumulative Energy Absorption

Equation-2 is obtained by integrating equation-1 in time after multiplying $\dot{x}$ for both side of the equation-1. Equation-3 indicates viscous-damping coefficient, when h is damping factor (fraction of critical damping) and k is stiffness. Equation-2 can be rewritten to equation-5 using equation-4 for simplicity. E_V, E_D, E_H , E_{pd} and E_I in the equation-4 is kinetic energy of masses, absorbed energies by viscous-damping, capacity of energy absorption by elasto-plastic response hysteresis, energy by P-delta effect and input energy for masses. Equation-6 and equation-7 are rewritten from equation-5. E_I and E_V are obtained from equation-4 using m, $\ddot{x}, \dot{x}, x, \ddot{y}$. Shaking table test provides $E_D + E_H$ from equation-6. E_D is obtained from equation-4 using c and $\dot{x}$. Capacity of energy absorption E_H by elasto-plastic response hysteresis is obtained from equation-7. E_{pd} is able to neglect in calculation of capacity of energy absorption, because P-delta effect will not absorb energy. Consequently, E_H is calculated from equation-9.

$$\int m\ddot{x}\dot{x}dt + \int c\dot{x}\dot{x}dt + \int kx\dot{x}dt - \int mg\frac{x}{L}\dot{x}dt = -\int m\ddot{y}\dot{x}dt \tag{2}$$

$$c = 2h\sqrt{km} \tag{3}$$

$$E_V = \int m\ddot{x}\dot{x}dt \quad , E_D = \int c\dot{x}\dot{x}dt,\ \ E_H = \int kx\dot{x}dt,\ \ E_{Pd} = -\int mg\frac{x}{L}\dot{x}dt\ , E_I = -\int m\ddot{y}\dot{x}dt \tag{4}$$

$$E_V + E_D + E_H + E_{Pd} = E_I \tag{5}$$

$$E_D + E_H = E_I - E_V - E_{Pd} \tag{6}$$

$$E_H = E_I - E_V - E_{Pd} - E_D \tag{7}$$

$$\text{while, } E_{Pd} \approx 0 \tag{8}$$

$$E_H = E_I - E_V - E_D \tag{9}$$

Energy-based Design using Housner's Assumption

Equation-10 indicates assumption proposed by Housner [3]. E_H and S_V is capacities of energy absorption of the structures and velocities obtained from pseudo-velocity response spectrum of input ground motions.

$$E_H \cong \frac{1}{2}mS_V{}^2 \tag{10}$$

$$V_D = \sqrt{\frac{2E_H}{m}} \tag{11}$$

$$E_H \geq \frac{1}{2}mS_V{}^2 \tag{12}$$

$$V_D \geq S_V \tag{13}$$

When we use Housner's assumption, velocities V_D are derived from equation-11. V_D is velocities converted from capacities of energy absorption. Required capacities of energy absorption E_H are defined by equation-12, as S_V is required (target) design velocity obtained from pseudo-velocity response spectrum. Energy-based design using Housner's assumption is described in equation-13.

EXPERIMENTS

Specimens

Nailed plywood shear walls of Japanese conventional post and beam structures were used for specimens. The specimens has two 910mm width nailed plywood panels and a 1820mm width opening between two nailed plywood panels that is shown in figure-1. Top and bottom of columns are connected to beams and sills using hold-down connectors.

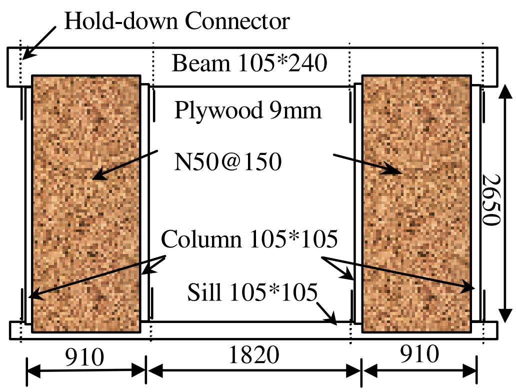

Fig.1 Specimens of Nailed Plywood Shear Walls

Shaking Table Test

NS component of JMA Kobe records during 1995 Kobe Earthquake was used for uniaxial shaking table test. The maximum acceleration, velocity, displacement of the record is 817cm/s^2, 90cm/s, 20cm respectively. Input motions used for shaking table test were normal motions of the record. In order to evaluate effect of phases of input motions, reverse motion of the record was also used by Yamaguchi [4]. Moving frame was used in order not to apply vertical loads to specimens. Design base shear coefficient of allowable strength design methods is described in equation-14. C_0 is design base shear coefficient. P_{al} is allowable shear-strength of specimens. m is masses of weights. Three weight conditions corresponding to design base shear coefficients 0.3, 0.4 and 0.5 were used. Consequently, test conditions of Test No.1,2,3 use 0.3, 0.4 and 0.5 for design base shear coefficients and the normal motion. Test condition of Test No.4 uses 0.3 for design base shear coefficients and the reverse motion.

$$C_0 = \frac{P_{al}}{mg} \tag{14}$$

RESULTS AND DISCUSSIONS

Load – Deformation Curves using P-delta forces and Non-linear Damping

Loads kx of specimens were calculated by equation-15. Third term in right side of equation-15 indicates forces of P-delta effect.

$$kx = -\left\{ m(\ddot{x} + \ddot{y}) + c\dot{x} - mg\frac{x}{L} \right\} \tag{15}$$

Response hysteresis curves of load (kx)-deformation relationship in Test No.1 to Test No.4 are shown in figure-2 to figure-5. "Original" curves in these figures use 2% for damping factor h. These constant damping are called linear damping (L.D.). "Original" curves are neglecting forces of P-delta effects in equation-15. "P-d + N.L.D." curves use forces of P-delta effects and non-linear damping factor (N.L.D.) which is assumed 2% before the maximum strength point and 0.2% after the maximum strength points. "P-Delta Force" curves show values of third term in right side of equation-15. When design base shear coefficients are 0.3 and 0.4 in figure-2, figure-3 and figure-5, response curves exceed their peak strength points and the energy absorption capacities are lost completely. Those are recognized as collapsed. When design base shear was 0.5 in figure-4, response curves do not exceed their peak strengths. Those are recognized as not collapsed.

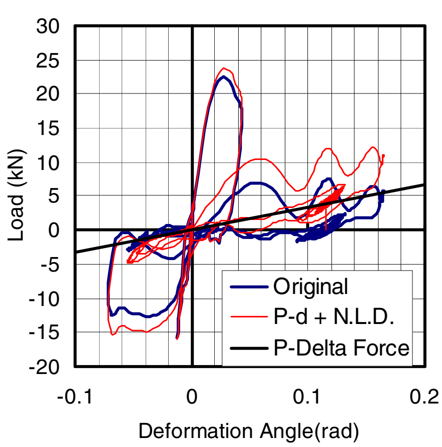

Fig.2 Load-Deformation Curves in Test No.1 (Normal Motion & C_0=0.3)

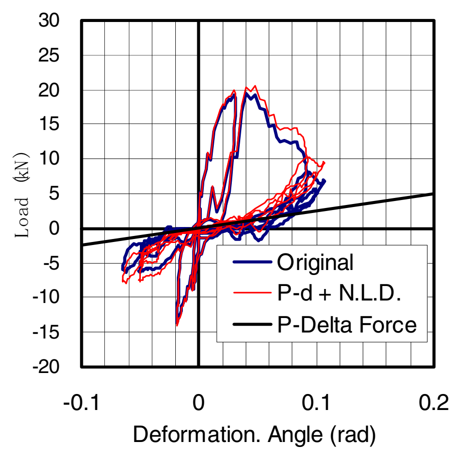

Fig.3 Load-Deformation Curves in Test No.2 (Normal Motion & C_0=0.4)

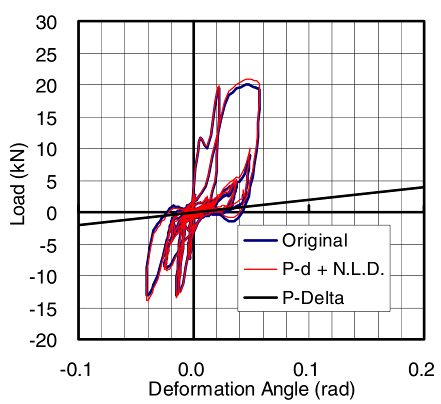

Fig.4 Load-Deformation Curves in Test No.3 (Normal Motion & C_0=0.5)

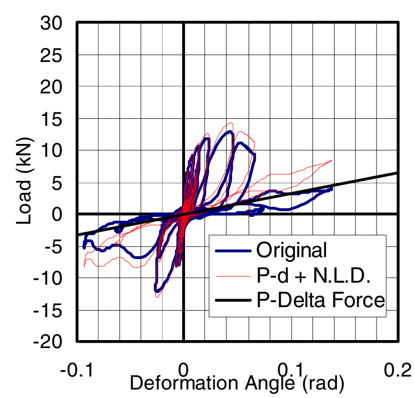

Fig.5 Load-Deformation Curves in Test No.4 (Reverse Motion & C_0=0.3)

Basic Asymmetrical Hysteresis Model and Energy Absorption Features

Response hysteresis after the peak strength points or dynamic yield points in shaking table test was translated into basic asymmetrical hysteresis model by Yamaguchi [5]. That is shown in figure-6. Asymmetrical energy absorption features are observed in figure-2 to figure-5. The capacity of energy absorption is indicated as inside area in the curves. After the response curve exceeds the peak strength points, the capacity of energy absorption on positive deformation side is not valid to absorb energy on negative deformation side. Failure (pulling out and/or punching out) of nails causes these energy absorption gaps on the response hysteresis. These energy absorption gaps do not appear before the peak strength points or dynamic yield points. It is suggested that these failure modes dominate response features after the peak strength points or dynamic yield points.

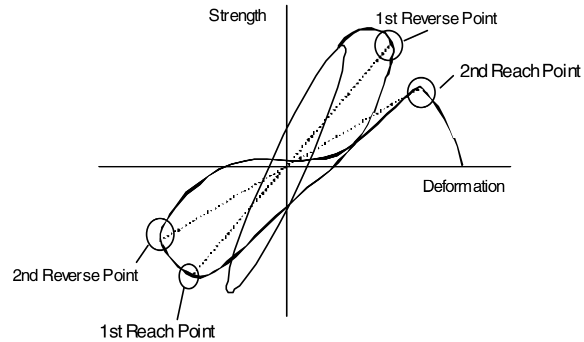

Fig.6 Basic Asymmetrical Hysteresisi Model

Process of Energy absorption

Input energy for masses E_I, cumulative energy absorption $E_I - E_V$, E_D(L.D.), E_D(N.L.D) and $E_I - E_V - E_{Pd}$ are calculated from equation-4 and equation-6. E_D(L.D.) and E_D(N.L.D) are cumulative energy absorption using linear and non-linear viscous damping factors. Figure-7 and figure-8 show time history curves of these energies when design base shear coefficients are 0.3 and 0.5 by the normal motion. In figure-7, E_I is distributed to E_V and E_H temporarily at some peaks of E_I, and E_V is released soon by decrease of E_I and increase of E_H. After E_{Pd} appears and disappear around 5.5 seconds in figure-7, E_I curve becomes less than E_I-E_V curve. That means the start of collapse where absorbed energy become unbalance to input energy. After 9 seconds, E_{Pd} appears again, and does not disappear. That is the completion of collapse by P-delta forces. In figure-8, E_V also appears at some peaks of E_I curves. E_{Pd} does not appear in figure-8, and finally E_I curve approach to E_I-E_V curve. Absorbed energy $E_D + E_H$ is balanced to input energy E_I. That means the specimen does not collapse.

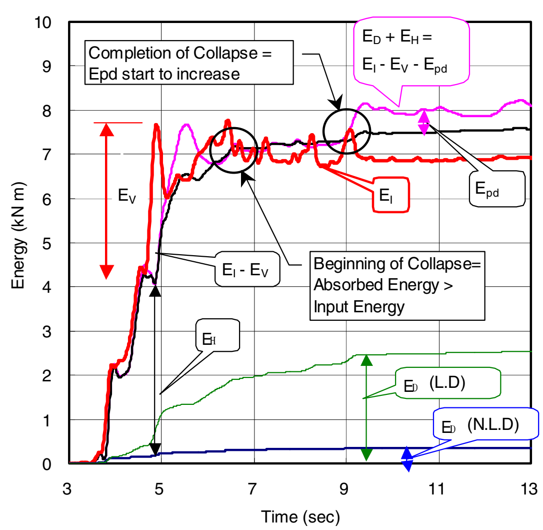

Fig.7 Cumulatibe Energies in Test No.1 (Normal Motion & C_0=0.3)

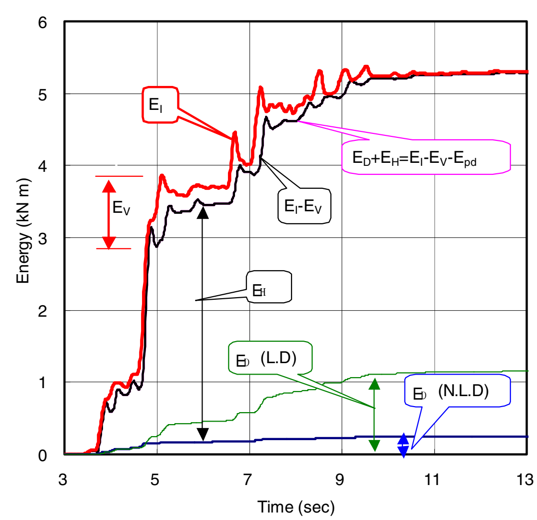

Fig.8 Cumulative Energies in Test No.3 (Normal Motion & C_0=0.5)

Collapse Analysis using Capacity of Energy Absorption

Velocities V_D converted from capacities of energy absorption E_H is shown in figure-9 to figure-12. These curves are calculated from equation-9 and equation-11, neglecting P-delta forces. Both of velocities VD(L.D.) and VD(N.L.D.) in figure-9 to figure-12 use linear damping factor and non-linear damping factor respectively. Because damping factor h should decrease after the specimens have damage, VD(N.L.D.) is suitable than VD(L.D.) for these collapse analysis. SV in figure-9 to figure-12 are velocity obtained from natural frequency of specimens and pseudo-velocity response spectrum of input ground motions. Natural periods of structures are calculated from secant stiffness on allowable strength points. Time history records of response acceleration and displacement are also shown in figure-9 to figure-12. In figure-9, VD(N.L.D.) is less than SV(224cm/s). Capacities of energy absorption don't satisfy required velocity of input motion. Then the specimen collapsed in Test No.1. In figure-10, VD(N.L.D.) is close to SV(234cm/s). Capacities of energy absorption almost satisfy required velocity of input motion. Then the specimen nearly collapsed in Test No.2. In figure-11, VD(N.L.D.) is greater than SV(185cm/s). Capacities of energy absorption satisfy required velocity of input motion. Then the specimen didn't collapse in Test No.3. In figure-12, VD(N.L.D.) is less than SV(266cm/s). Capacities of energy absorption don't satisfy required velocity of input motion. Then the specimen collapsed in Test No.4.

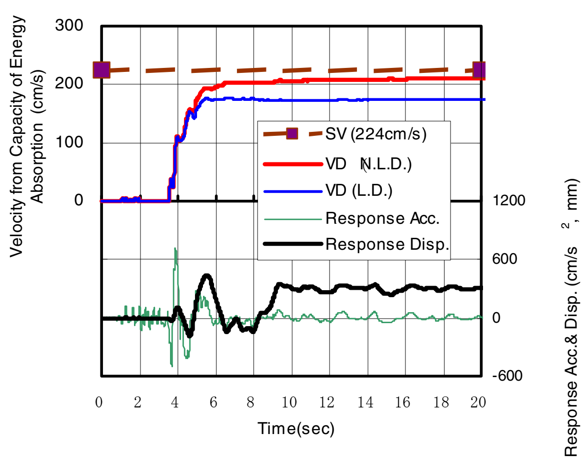

Fig.9 S_V , V_D and Response of Acc. & Disp. in Test No.1 (Normal Motion & C_0=0.3)

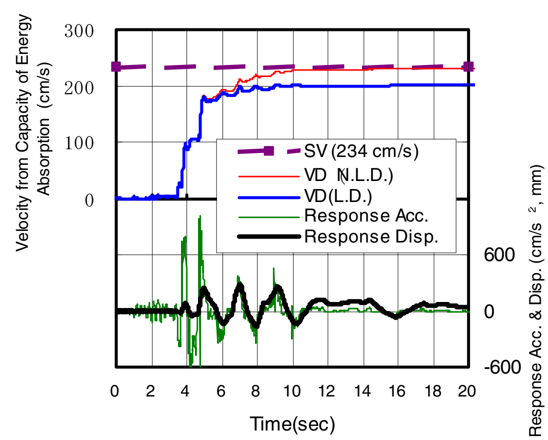

Fig.10 S_V , V_D and Response of Acc. & Disp. in Test No.2 (Normal Motion & C_0=0.4)

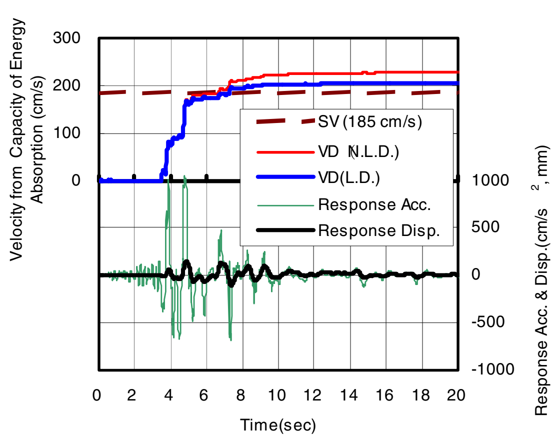

Fig. 11 S_V , V_D and Response of Acc. & Disp. in Test No.3 (Normal Motion & C_0=0.5)

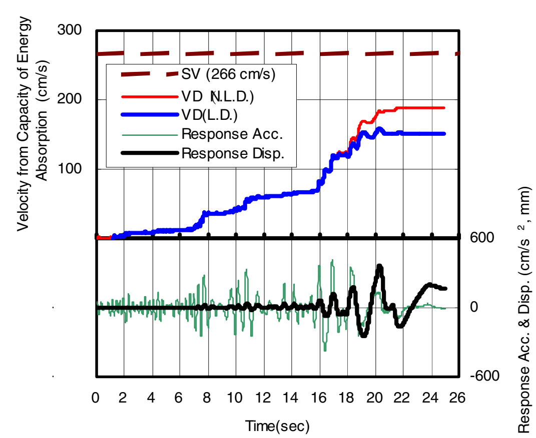

Fig.12 S_V , V_D and Response of Acc. & Disp. in Test No.4 (Reverse Motion & C_0=0.3)

Verification of Energy-based Design using Housner's Assumption

Relationship between SV and VD are summarized in table-1. When velocities response spectrum S_V is greater than velocities V_D, test results are "Collapse". When S_V is less than V_D, test results is "Not Collapse". These results satisfy equation-10 to equation-13 that include Housner's assumption. Energy-based design using Housner's assumption was verified for timber structures in these tests.

Table 1 Relationship of S_V , V_D and Test Results

Test No.	Input Motion	Weight Condition	Velocity Response Spectrum of Input Motion		Capacity of Energy Absorption		Verification of Housner's Assumption		Test Results
	1995 JMA Kobe	Base Shear C_0	T (sec)	S_V (h=0.02) (cm/s)	V_D (cm/s)	V_{D-m} (cm/s)	S_V / V_D ratio	V_D / V_{D-m} ratio	
1	Normal	0.3	0.55	224	210	157	1.07	1.33	Collapse
2	Normal	0.4	0.47	234	231	182	1.01	1.27	Nearly Collapse
3	Normal	0.5	0.42	185	228	203	0.81	1.13	Not Collapse
4	Reverse	0.3	0.55	266	189	157	1.41	1.20	Collapse

Capacities on Asymmetrical Hysteresis Model

Instead of capacities of energy absorption V_D that is obtained from shaking table test, V_{D-m} is proposed which is obtained from capacities on aforesaid basic asymmetrical hysteresis model. Capacities on asymmetrical hysteresis model are shown in figure-13 and figure-14. Inside area of asymmetrical envelope lines on load-deformation curves is defined for capacities on asymmetrical hysteresis model, because the energy absorption features are asymmetrical after dynamic yield or the maximum strength points. It was reported by Yamaguchi [6]. This capacity of energy absorption is also obtained from load-deformation curves by standard racking test, instead of shaking table test. Capacity of energy absorption on asymmetrical model is obtained by the following procedures. Simplified envelope lines connect continuously between negative peak strength points, negative dynamic yield points, origins, positive dynamic yield points, positive peak strength points and strength zero points. Standard yield points in racking test are possible to use instead of dynamic yield points. Capacity of energy absorption on asymmetrical hysteresis model is obtained from inside area of these simplified envelope lines.

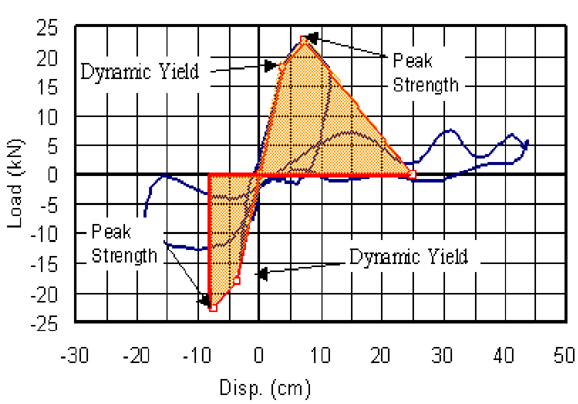

Fig.13 Capacities on Asymmetrical Hysteresis Model from Test No.1 (Normal Motion)

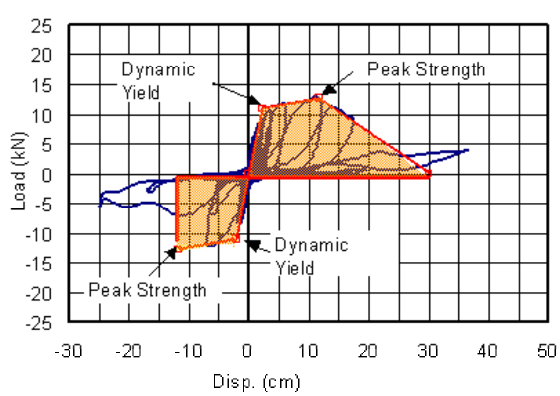

Fig.14 Capacities on Asymmetrical Hysteresis Model from Test No.4 (Reverse Motion)

Application of Energy-based Design for Survivability Limit State Criteria

Figure-7 and figure-8 indicate process of energy absorption on E_V, E_D, E_H , E_{pd} and E_I. Figure-9 to figure-12 indicate relationship between capacities of energy absorption and collapse. These data can establish limit state criteria based on energies. A limit state definition including survivability limit state had been proposed by Dowrick [7]. Table-2 is a new proposal of survivability limit state criteria based on energies. Criteria of survivability limit state using capacity of energy absorption is proposed in table-2. Aforesaid capacities of asymmetrical hysteresis model V_{D-m} is used for this criterion. V_{D-m} can be obtained from standard racking tests and is a little conservative than V_D obtained from shaking table tests. Application of energy-based design using V_{D-m} is proposed for survivability limit state criteria.

Table 2 Limit State Criteria based on Energies

<table>
<tr><td>Lank</td><td>A</td><td>B</td><td>C</td></tr>
<tr><td>Limit State</td><td>Serviceability</td><td>Safety</td><td>Survivability</td></tr>
<tr><td rowspan="2">Damage</td><td>Undamage of Structure</td><td>Undamage of People</td><td>Survivable of People from Disaster</td></tr>
<tr><td>Repairable of Structure</td><td>Damage of Structure</td><td>Uncollapse of Structure</td></tr>
<tr><td>Design Criteria for Vertical Load</td><td>Allowable Strength</td><td>Ultimate Strength</td><td>Pre-collapse</td></tr>
<tr><td rowspan="8">Design Criteria for Seismic Load</td><td colspan="2">Strength-Based Criteria</td><td rowspan="5"></td></tr>
<tr><td>Py: Allowable Strength</td><td>Pu: Ultimate Strength (0.8*Pmax)</td></tr>
<tr><td>Pre-Yield</td><td>Post-yield</td></tr>
<tr><td colspan="2">Displacement-Based Criteria</td></tr>
<tr><td>Dy: Allowable Displacement</td><td>Du: Ultimate Displacement</td></tr>
<tr><td rowspan="3"></td><td colspan="2">Energy-Based Criteria</td></tr>
<tr><td colspan="2">by Plastic Deformation</td></tr>
<tr><td></td><td>V_{D-m} : Capacity of Energy Absorption on Asymmetrical Hysteresis Model</td></tr>
</table>

CONCLUSIONS

In order to develop energy based evaluation method of seismic performance of timber structures, a series of shaking table test of shear walls was conducted.

Effect of P-delta forces and non-linear damping was considered in load-deformation curves in shaking table tests.

Asymmetrical hysteresis model was proposed and its energy absorption features were described.

Process of energy absorption and distribution between energies in the equation was analyzed.

Relationship between capacities of energy absorption and collapse was clarified.

Energy-based design method using Housner's assumption was verified in shaking table tests of timber structures.

Capacities of asymmetrical hysteresis model V_{D-m} were defined.

Application of energy-based design using V_{D-m} is proposed for survivability limit state criteria.

REFERENCES

1. Akiyama H., *Earthquake-resistant Design Method for Buildings Based on Energy Balance*, Gihoudou Syuppan Press. Nov.1999
2. Yamaguchi N., Minowa C., “Dynamic Performance of Wooden Bearing Walls by Shaking Table Test”, *Proceedings of Fifth World Conference on Timber Engineering-Volume 2*, EPF Lausanne, Switzerland, August 1998, pp.26-33
3. Housner G.W., “Limit Design of Structures to Resist Earthquake”, *Proceedings of First World Conference on Earthquake Engineering*, San Francisco, 1956, pp. 5-1 to 5-13.
4. Yamaguchi N., Minowa C., “ Evaluation of Dynamic Performance of Wooden Bearing Walls by Shaking Table Test - No.5 Evaluation using Energy and Response by Reverse Earthquake Motion”, *Summaries of Technical Papers of Annual Meeting (1999)- Structure 3*, Architectural Institute of Japan, Sep. 1999, pp.229-230.
5. Yamaguchi N., Minowa C., “Evaluation of Dynamic Performance of Wooden Bearing Walls by Shaking Table Test - No.1 Dynamic Hysteresis Loops of Plywood Walls ”, *Summaries of Technical Papers of Annual Meeting (1997)-Structure 3*, Architectural Institute of Japan, Sep. 1997, pp.143-144.
6. Yamaguchi N., Minowa C., “Evaluation Method of Seismic Performance using Energy Absorption Capacity”, *Proceedings of IABSE Conference Lahti 2001- Innovated Wooden Structures and Bridges*, IABSE REPORT Volume 85, Lahti, Finland, August 2001, pp.423-428
7. Dowrick D., “Criteria for earthquake resistant design”, *Earthquake Resistant Design*, John Wiley & Sons, Oct., 1990, pp.142-148