A SEICMIC UPGRADING TECHNIQUE FOR TIMBER STRUCURE WITH VISCO-ELASTIC TAPE

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ABSTRACT:

For the purpose of encouraging to seismically upgrade existent timber houses, we develop a newly simple and economical technique to improve seismic performance of timber houses by installing visco-elastic tape between columns, beams and boards made of gypsum and plywood.
Vibration performance tests of simple substance of visco-elastic tape and shaking table tests of timber frame reinforced by visco-elastic tape are conducted to confirm the efficiency of this technique. For shaking table tests, test frames of gypsum board and plywood board are prepared with and without visco-elastic tape. We mainly discuss the results by equivalent viscous damping and strength of test frame that are calculated from load-deformation relations. Test results show considerable improvement of seismic performance due to visco-elastic tape. Dynamic characteristics of visco-elastic tape are mathematically modeled. Prediction technique is also proposed for a seismic upgrading design by visco-elastic tape. Predicted results meet good agreement with test results.

KEYWORDS: Timber structure, visco-elastic tape, shaking table test, seismic upgrading technique

1. INTRODUCTION

In the 1995 Hyogoken-Nambu earthquake, lots of old vulnerable timber houses have been collapsed or severely damaged. In Japan, although there are still a large number of people living in old timber houses, many of them are not confirmed to have enough seismic performance for future earthquake. In such a situation, development of simple and economical techniques for improvement of seismic performance of timber houses attracts people’s attention. We develop a newly simple and economical technique to improve seismic performance of timber houses by installing visco-elastic tape between columns, beams and boards made of gypsum and plywood.
In order to confirm the efficiency of this technique, we conduct two kinds of tests. First is vibration performance test of visco-elastic tape to grasp fundamental dynamic characteristics. Based on the test results, analytical model of the visco-elastic tape is mathematically proposed. Second is shaking table test of timber frame subjected to sinusoidal wave excitation. Two types of timber frame with gypsum board and plywood board are prepared for shaking table test. Dynamic characteristics of test frames reinforced by visco-elactic tape are discussed by comparison to the results of test frames without visco-elactic tape. Following the discussion of test results, prediction of seismic performance for timber frame reinforced by visco-elastic tape is proposed.

2. UPGRADING TECHNIQUE WITH VISCO-ELASTIC TAPE

Adhesive tape adopted as seismic upgrading material in this study is butyl-rubber type visco-elastic medium of which thickness is 1mm. Any other adhesive materials are not required for the construction of this technique. It is because visco-elastic tape itself has enough adhesive capacity. Figure 1 shows photo of visco-elastic tape and schematic figure of timber frame where visco-elastic tape is installed. Visco-elastic tape is installed between board and columns of timber frame system. When the system is subjected to shaking due to external excitement such as earthquake, frame produces shearing deformation. On the other hand, board produces rotational deformation because board is usually assumed rigid body. Therefore, shearing deformation relatively occurs between frame and board. As a result, timber frame system dissipates energy due to shearing deformation of visco-elastic tape, and seismic response of timber frame system decreases consecutively. Strength and stiffness of timber frame system are also expected to increase by installing visco-elastic tape as well as hysteresis energy consumption.

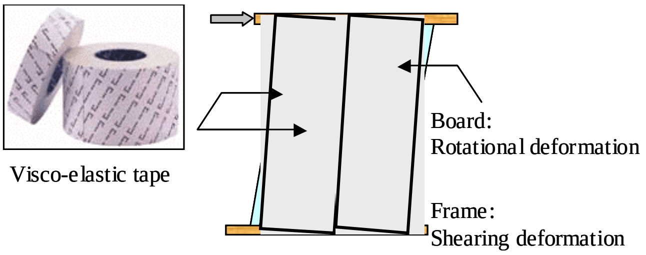


Figure 1 Schematic figure of timber frame reinforced by visco-elastic tape

3. VIBRATION PERFORMANCE TEST OF VISCO-ELASTIC TAPE

3.1. Outline of the Test

Vibration performance test is conducted to understand fundamental characteristics of simple substance of visco-elastic tape. Figure 2 shows universal testing apparatus in which test piece is placed. Vsico-elastic tapes (30x100x1mm) attached between two veneer plates are inserted into the set of steel plate jig. Direction of vibration is vertical in Figure 2. Considering temperature dependency of visco-elastic tape, test is conducted under the condition of three kinds of outside air temperature (10, 20, 30 and 40 degree of Celsius). Moreover, three test pieces are prepared for each temperature, considering the fluctuation of test piece characteristics.

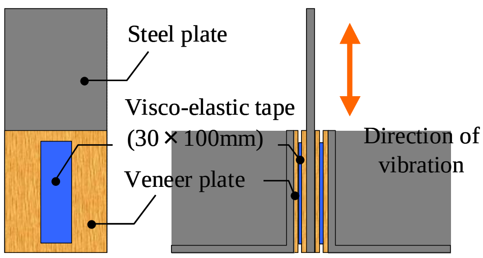


Figure 2 Test apparatus of vibration performance test of visco-elastic tape

3.2. Results of the Test

Figure 3 shows temperature dependency of visco-elastic tape on equivalent stiffness and hysteresis energy consumption. Results of all the temperatures are scaled by those of 20 degree.

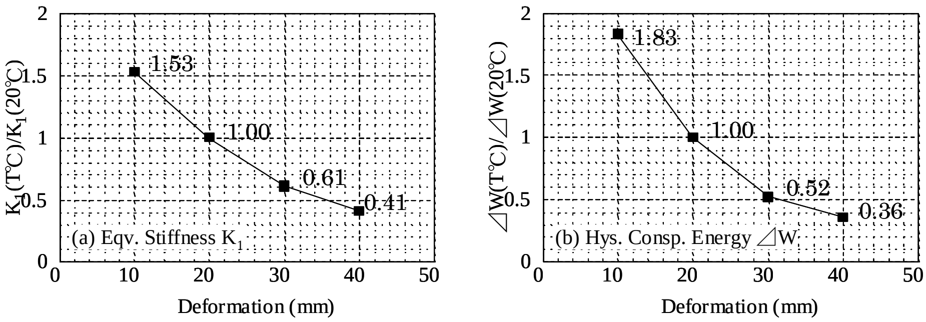


Figure 3 Temperature dependency of visco-elastic tape

Results indicates that both equivalent stiffness and hysteresis energy consumption decrease to about 60% in case of 30 degree, and about 40% in case of 40 degree, compared to the results of 20 degree. It clearly shows temperature dependency of mechanical characteristics of visco-elastic tape.

3.3. Mathematical Modeling of Visco-elastic Tape

Based on the vibration performance test results, mathematical model of visco-elastic tape is established by use of traditional visco-elastic theory. Mathematical model is assumed to four-element visco-elastic model [1][2]. Real part K_1, and imaginary part K_2 of complex modulus of four-element viscous medium are expressed in Eqn.3.1. Equivalent viscous damping is also described in Eqn.3.2. First, parameters k_M, k_K, c_M, and c_K defined in Figure 4 in case of 20 degree are determined from the test results. Parameters k_M, k_K, c_M, and c_K of 20 degree are referred to as norm to express temperature dependency on the test results in other temperature. Next, the parameters of mathematical model of other temperatures are identified using the test results. Based on the identified parameters in all the temperature, visco-elastic tape is mathematically modeled as four-element visco-elastic medium shown in Eqn.3.3 and 3.4. Figure 5 shows the load-deformation relations (20 degree) of test results and mathematically predicted results from Eqn.3.1 and 3.4. Predicted load-deformation relations meet good agreement with the test results. It should be noted that load-deformation relations shows dependency on temperature and amplitude, indicating decrease of gradient of hysteresis loop.

$$K_1 = \frac{P_1}{\delta_{\max}} = \frac{\omega^2 k_M c_M{}^2}{\omega^2 c_M{}^2 + k_M{}^2} + k_K \qquad K_2 = \frac{P_2}{\delta_{\max}} = \frac{\omega k_M{}^2 c_M}{\omega^2 c_M{}^2 + k_M{}^2} + \omega c_K \tag{3.1}$$

$$heq = \frac{1}{4\pi} \cdot \frac{\Delta W}{We} \tag{3.2}$$

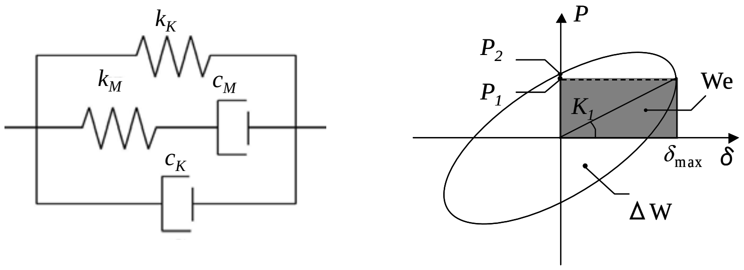


Figure 4 Schematic figure of four-element visco-elastic model and its hysteresis loop

$$k_K = 17.24\gamma^{-0.628} e^{-0.050T} \qquad k_M = 628.24\gamma^{-0.471} e^{-0.050T} \tag{3.3}$$

$$c_M = 92.32\gamma^{-0.401} e^{-0.050T} \qquad c_K = (14.73 - 103.83\gamma^{-0.363} e^{-\frac{\omega}{4.82}}) e^{-0.050T} \tag{3.4}$$

where, $\delta_{\max}$ is the maximum deformation, P_1 is load at the maximum deformation, P_2 is load when the deformation is zero, ω is circular frequency, γ is shearing strain, and T is temperature.

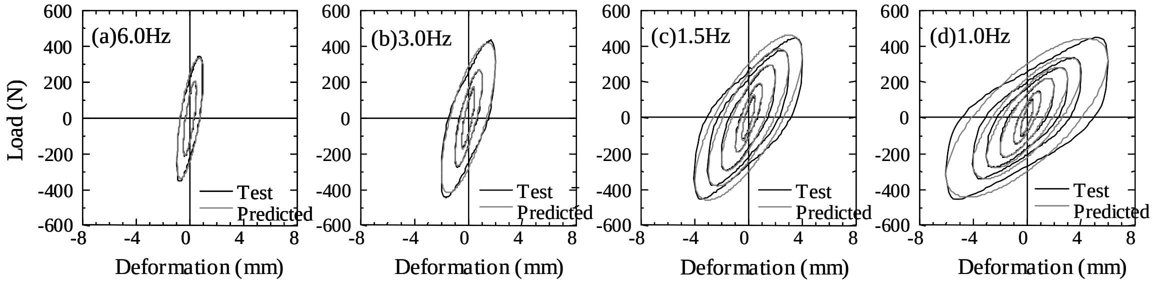


Figure 5 Load-deformation relations (Test results versus predicted results)

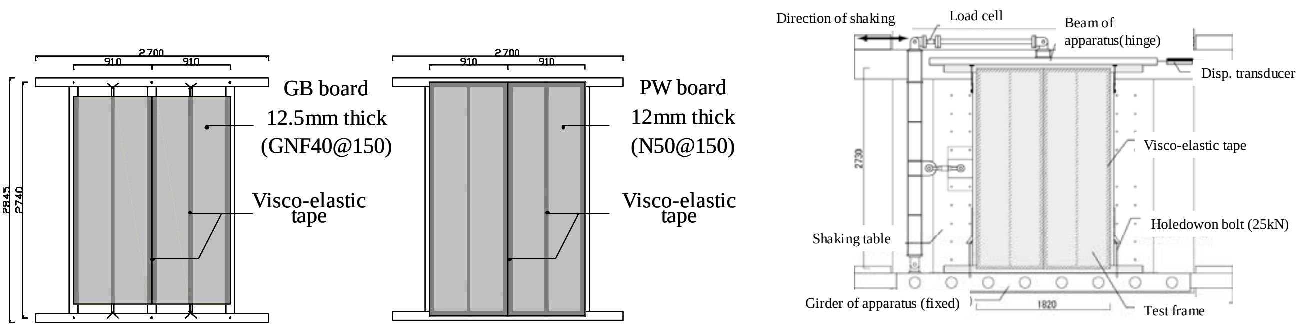
4.SHAKING TABLE TEST OF TIMBER FRAME WITH VISCO-ELASTIC TAPE

4.1. Outline of the Test

We conduct shaking table test to study dynamic characteristics of realistic large-scale timber frame reinforced by visco-elastic tape. In the shaking table test of this section, sinusoidal wave is adopted as input motion. Test frames are as large as 2P x 3P (P=910mm), based on realistic timber house frame. Table 4.1 indicates the details of test frames that are categorized into two groups. One is the group of test frames installing gypsum board that is expected to reinforce the interior wall. This type of test frame holds the gaps at the top and the bottom of the test frame taking into account the existence of ceiling and floor. Another one is the group of test frames installing plywood board that is expected to reinforce the exterior wall. This type of test frame doesn’t have any gaps. Test frame reinforced by visco-elastic tape is compared to that without it. Gypsum board and plywood board are placed into frame by nailing. In the following, gypsum board test frames are called GB series, and plywood board test frames are called PW series. Figure 6 shows samples of GB and PW test frame, and shaking table test apparatus. Visco-elastic tape for GB series is installed between board and columns or studs, of which adhesive length is about 2420mm. On the other hand, visco-elastic tape for PW series is installed between board and beams or girders (adhesive length is about 910mm) as well as columns or studs (adhesive length is about 2730mm). Board is placed into frame by nailing and visco-elastic tape for reinforced test frame. Considering temperature dependency of visco-elastic tape, series of this shaking table test are conducted in the condition of 10, 20, and 30 degree of Celsius.

Table 4.1 Details of test frames

Test frame	Board	Nail	Tape
GB-T(℃)	Gypsum board	GNF40@150	None
GB＋tape-T(℃)	910×2420×12.5㎜		$629.2\times10mm^2$
PW-T(℃)	Plywood board	N50@50	None
PW＋tape-T(℃)	910×2730×12㎜		$794.3\times10mm^2$



(a) ‘GB+tape’ test frame (b) ‘PW+tape’ test frame (c) Test apparatus for shaking table test

Figure 6 Sample of Test frame (a) GB series and (b) PW series, and (c) test apparatus

Test frame is placed into apparatus and fixed to steel beam and girder of the apparatus by six sets of bolt at each. Beam of the apparatus prepares ball bearing at its bottom face for parallel movement according to excitement from shaking table. Beam of the apparatus is connected to girder at one side by steel column, so movement of test frame column in perpendicular direction to shaking direction is considered. Therefore, the tops and tips at columns of test frame are reinforced by anchor bolts to firm the joint of test frame. Assuming natural frequency of typical timber house 3Hz at the 1/120 radian of drift angle, cycles of shaking table test are determined [3].

4.2. Load-deformation Relations

Figure 7 shows load-deformation relations of GB and PW series. Results with visco-elastic tape are compared to those without visco-elastic tape. In GB series, at the drift angle of 1/120 rad., cracks begin to occur around the corner of gypsum board, and nails begin to be pulled out. Thereafter, the extent of damage became large, and gypsum board begin to move in out-of-plane direction.

In PW series, some nails begin to be pulled out at the drift angle of 1/60 rad., and almost all the nails are pulled out at 1/30 rad.. Large degradation of maximum strength reflects this phenomenon. Many of nails of plywood board show failure by pulling out, on the other hand, nails of plywood reinforced by visco-elastic tape has tendency to be just pull out without any failure.

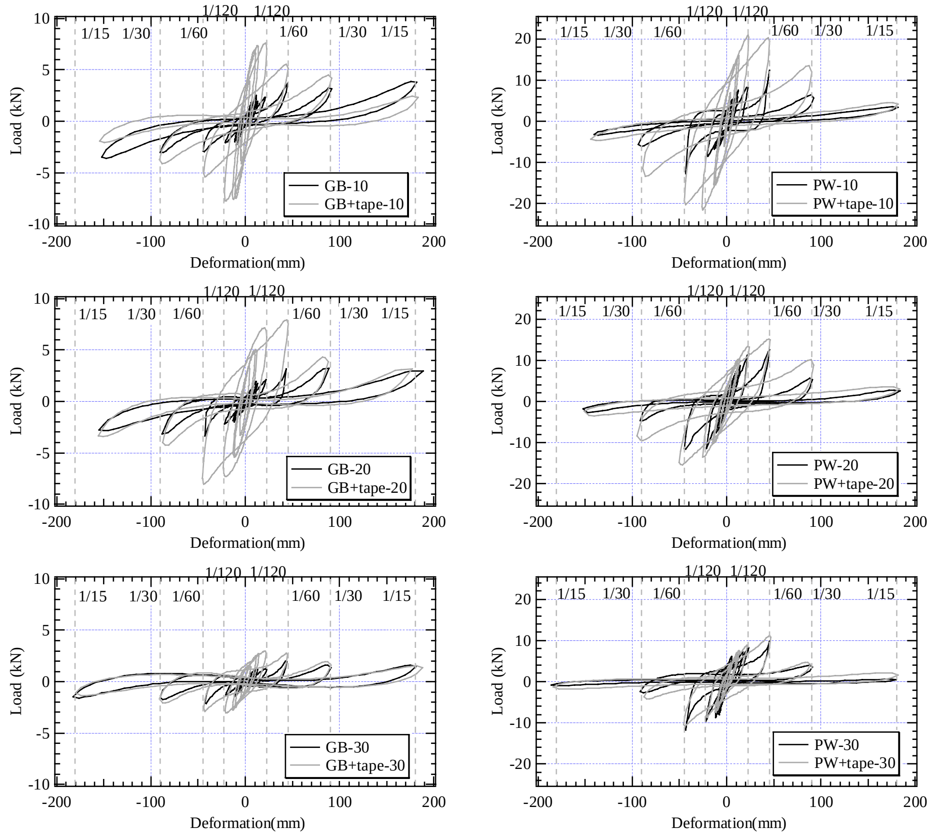


Figure 7 Shaking table test results: Load-deformation relations of GB and PW series

Strength at each cycle of GB and PW series test frames reinforced by visco-elastic tape considerably increases, compared to the result without visco-elastic tape. Loop areas surrounded by each cycle of test frames reinforced by visco-elastic tape become much larger than those without visco-elastic tape. This result shows visco-elastic tape can add more strength and hysteresis energy consumption to the test frame. This tendency of the upgrading effect for seismic resistance is outstanding especially in the condition of 10 and 20 degree in Celsius. While we can confirm significant upgrading effect up to the extent of drift angle of about 1/60 rad., any important difference between with and without visco-elastic tape cannot be observed in large deformation. This can be explained by the large extent of shearing strain of visco-elastic tape of over 500% that is supposed to the limit of elastic deformation of visco-elastic medium in usual. At this large extent of deformation, visco-elastic tape itself may be damaged, or detached from columns and studs. Gypsum board and plywood board are damaged and attachment of board become loose due to extract of nails. Those phenomena may show the decrease of adhesive of visco-elastic tape and result in degrading the upgrading effect. Even though little increase of performance in large deformation can be seen, significant upgrading effect due to visco-elastic tape can be expected up to considerable deformation corresponding to the moderate earthquakes. Load-deformation relations also show temperature dependency of test frames reinforced by visco-elastic tape.

4.3. Comparison of Upgrading Effect Due to Visco-elastic Tape

Equivalent viscous damping (heq) and equivalent strength of GB and PW series test frames are quantitatively compared in Figure 8 and 9 respectively. While test frame itself (without tape) indicates about 10 to 15% of heq, the extent of equivalent viscous damping of test frames with visco-elastic tape increases up to about 20%. Equivalent strength is derived by considering the damping effect of Figure 8. These results indicate significant improvement of seismic performance by visco-elastic tape.

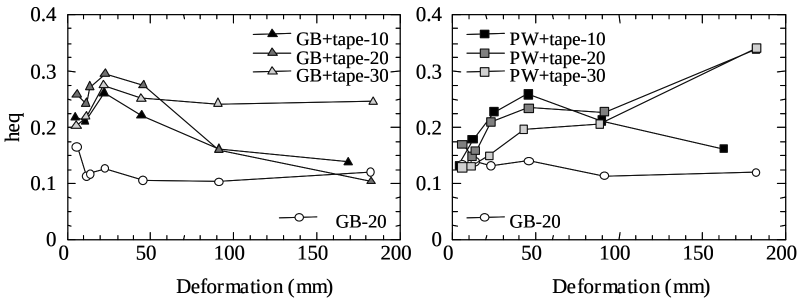


Figure 8 Equivalent viscous damping

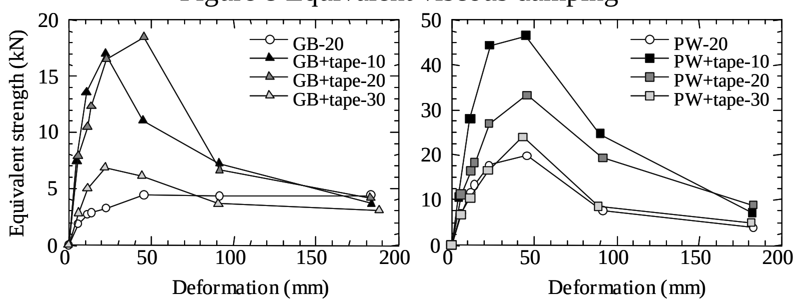
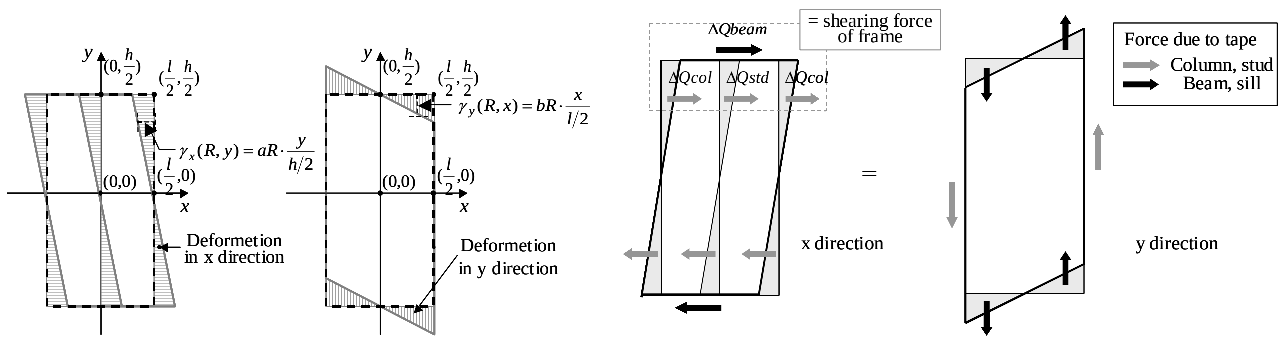


Figure 9 Equivalent stiffness

5. ESTIMATION OF UPGRADING EFFECT

For seismic upgrade design of timber structure reinforced by visco-elastic tape, upgrading effect should be theoretically predicted. In this section, upgrading effect due to visco-elastic tape is quantitatively estimated according to the test results of the previous section. Seismic resistant elements of test frame consist of 1) frame, 2) board, and 3) visco-elastic tape. Strength and hysteresis energy consumption of whole test frame derived from the test results are considered the accumulation of contribution of those elements. If dynamic characteristics of visco-elastic tape are understood, the effect of reinforcement by visco-elastic tape will be predicted. Accordingly, vibration performance test results of the tape in Section 2 can lead to the prediction of upgrading effect of whole test frame with visco-elastic tape. In the following, strength and hysteresis energy consumption are estimated.



(a) Distribution of deformation (b) Balance of forces in test frame with visco-elastic tape

Figure 10 Schematic figure of behavior of visco-elastic tape installed into test frame

Coordinates of board and distribution of deformation of visco-elastic tape are shown in Figure 10 (a). The origin of the coordinate axes is placed in the center of board. Shearing strain of visco-elastic tape γ_{xy} are expressed by the drift angle of frame R in Eqn.5.1. Scaling coefficients of a and b are the parameters geometrically obtained by the relations between the strain of the tape and the drift angle. Thereafter they are modified by the relative deformation of boards observed in the test of Section 4.

where, (5.1)

Some assumptions are made on the relations between deformations of frame and visco-elastic tape. While frame produces shearing deformation subjected to shaking, it can be assumed that board produces rotational deformation. Therefore, visco-elastic tape relatively deforms for balance of forces in x and y direction shown in Figure 10 (b). Force produced by the deformation in x direction balances with shearing force of frame, and can be assumed the added strength by reinforcement due to visco-elastic tape. According to the assumption above, increments of strength and hysteresis energy consumption by reinforcement of visco-elastic tape can be estimated in Eqn.5.2 and 5.3. Here, h is tape length, b tape width, t tape thickness, K_1 and K_2 are real and imaginary part of equivalent stiffness of visco-elastic tape that are already defined in Section 3, is shearing strain of visco-elastic tape, is strain in lateral direction (x direction) of visco-elastic tape.

(5.2)

(5.3)

Test results of Section 3 and 4 indicate that dynamic characteristics of visco-elastic tape are dependent on the amplitude of deformation as well as temperature. Magnitude of deformation tends to be locally distributed. Therefore, overall length of tape is divided into infinitesimal small elements to estimate the upgrading effect of test frame. Assuming visco-elastic tape to be four-element visco-elastic medium, total upgrading effect of the frame is estimated by adding the contribution of all the infinitesimal small elements. Ratios of the test results of strength and hysteresis energy consumption ( ) to the predicted results are shown in Figure 11. It should be noted that strength and hysteresis energy consumption in Figure 11 mean the difference between reinforced test frame (GB+tape and PW+tape) and reference test frame (GB and PW). They represent the increment of seismic performance by installing visco-elastic tape. Comparison of the predicted strength and hysteresis energy consumption to those from the test results indicates that the predicted results excessively estimate over 1/30 rad.. Therefore, based on the test results, modifications of prediction from test results are proposed by Eqn.5.4 and 5.5. Grey thick solid lines in Figure 11 represent the ratio α expressed by Eqn.5.4 and 5.5. The ratio α predicts the behavior of test frame with visco-elastic tap including modification based on the test results, and is derived from the test results in the condition of 20 degree in Celsius by least squares method. In case of GB series, considering that the upgrading effect cannot be observed over 1/30 rad., α is estimated within the range of 1/30 rad..

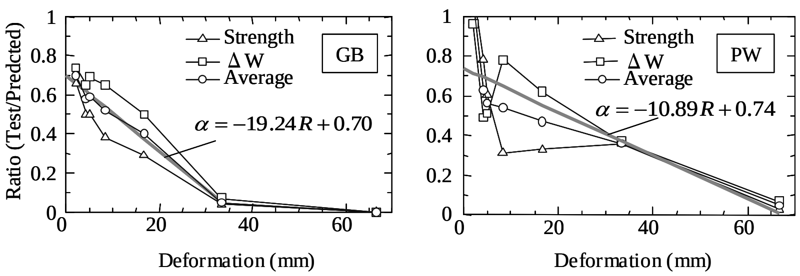


Figure 11 Ratios of test results to predicted results

GB series

(5.4)

PW series

(5.5)

Eqn.5.4 and 5.5 means that the predicted results should be degraded along with drift angle *R*, and the test results reach to 70% of the theoretically predicted results in the small range of drift angle. It may be because of the following reason. While prediction is based on the test results of vibration performance test in Section 3 where adhesive is good enough, fluctuation of adhesive can be spatially seen in case of large-scale test frame of the shaking table test.

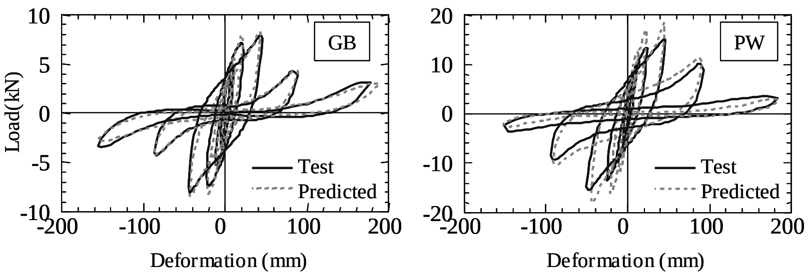


Figure 12 Comparison of predicted load-deformation relation to test result

Load-deformation relations predicted by Eqn.5.4 and 5.5 are shown in Figure 12 by comparison to test results of GB+tape and PW+tape of 20 degreein Celsius in Section 4. According to the results, prediction in this section meets good agreement with the test results of Section 4. It can be said that the proposed technique by Eqn.5.4 and 5.5 can predict the upgrading effect due to visco-elastic tape from the theoretical estimation.

6. CONCLUSIONS

In order to develop newly simple and economical seismic upgrading construction technique, we conduct vibration performance test of simple substance of visco-elastic tape and shaking table test of realistic large-scale timber frame reinforced by visco-elastic tape. Vibration performance test makes it clear that dynamic characteristics of visco-elastic tape are dependency on temperature and amplitude of deformation. Mathematical model of visco-elastic tape is developed by the results of the test.
Results of shaking table tests indicate that strength and hysteresis energy consumption are significantly improved for the extent of shaking amplitude corresponding to moderate earthquake.
Temperature dependency is also observed in the results of shaking table test, and outstanding in the condition of 10 and 20 degree in Celsius. Finally, technique of predicting upgrading effect due to visco-elastic tape is proposed. Predicted strength and hysteresis energy consumption meet good agreement with the results of shaking table test. Load-deformation relations are also accurately predicted.

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