A Study on Simplified Evaluation Method for Seismic Retrofit of Existing Wooden Houses

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SUMMRY:
In this paper, we introduce a new index, "the strength index for the seismic retrofit", into the seismic retrofit technique to simply evaluate the effect of the retrofit for the existing wooden houses. This index represents the amount of the strength, which is equivalent to reducing the mass, and to increasing the viscous damping or the stiffness after the yielding. First, we present the formulation of the index and the parameters agreed with the earthquake response spectra by considering three types of soil class prescribed in the Building Standard Law in Japan. Next, the application of the formulation is discussed. Furthermore, we propose a reinforcing element, which is considered as the hardening type of restoring force characteristics, to realize the seismic retrofit by increasing the stiffness after the yielding of the structure.

Keywords: Existing Wooden House, Seismic Retrofit, Strength index of Seismic Retrofit

1. INTRODUCTION

Destructive earthquakes have been occurring in Japan recently and as a result many buildings damaged. Enhancement of the earthquake resistant safety of buildings, especially the existing wooden houses, is very important to reduce the human damage during earthquakes. Therefore, the seismic diagnosis is getting carried out and the seismic retrofit for the existing wooden houses is also necessary.

In Japan, many kinds of the seismic diagnostic technique for wooden houses are prescribed, e.g., the Standard, the Horizontal Load-carrying Capacity, the Limit Strength Calculation and the Time History Response Analysis methods. They are intended for the working design of the seismic diagnosis and the seismic retrofit for the individual house. On the other hand, little attention has been given to a method to determine whether the seismic retrofit is possible for the individual house, and to evaluate the effect of the seismic retrofit for unspecified houses.

Several simplified methods are already introduced into the seismic diagnosis for the existing wooden houses, e.g., the formulation of the relationship between the natural periods, which is obtained from the microtremor measurement, and the seismic index, and of the relationship between the period and the horizontal load-carrying capacity. In this way, several studies have been made on the simplified seismic diagnostic method. Very few attempts, however, have been made at studies on the simplified evaluation technique for the seismic retrofit.

In this paper, we introduce a new index, "the strength index of the seismic retrofit", into the seismic retrofit technique to simply evaluate the effect of the seismic retrofit for the existing wooden houses. This index represents the amount of the strengthening, which is equivalent to reducing the mass, and to increasing the viscous damping or the stiffness after the yielding. Only the one-storied house model is considered.

First, we present the formulation of the index and the parameters agreed with the earthquake response spectra by considering three types of soil class prescribed in the Building Standard Law in Japan. Next, the application of the formulation is discussed. Furthermore, we propose a reinforcing element, which is considered as the hardening type of restoring force characteristics, to realize the seismic retrofit by increasing the stiffness after the yielding of the structure.

2. ANALYTICAL MODELS

We choose two house models listed in Table 2.1, which are the general one-storied wooden houses. The earthquake resisting elements of the conventional and the traditional houses are respectively the mud wall and the braced wall. The differences in both models are the weight and the yield angle of the restoring force characteristics.

Table 2.1. Parameters of Structural Model

		Conventional House Model	Traditional House Model
Weight, w		2.00 kN/m^2	2.50 kN/m^2
Height, H		3.00 m	
Restoring force Characteristics	Skeleton Curve	Bi-linear Type	
	Yield Angle, R_y	1/120 rad	1/60 rad
	Hysteresis Rule	Slip Type	
Damping Ratio, h_0		0.05	

Acceleration response spectra presented as following expression is introduced. This expression is modeled by the spectra prescribed in the Building Standard Law in Japan (BSLJ).

$$S_S = a_1 \cdot \left(e^{-a_2 \cdot T} - e^{-a_3 \cdot T}\right) + a_4 \tag{2.1}$$

where, S_s is the acceleration spectrum on the ground level, T the period of the structure, a_i the parameters which decides the shape corresponds to three kinds of the site specific response spectra. The parameters a_i are listed in Table 2.2, and the schemes of the spectra are shown in Fig. 2.1.

Table 2.2. Parameters of Acceleration Spectra

Soil class	a_1	a_2	a_3	a_4
I	18.685	1.206	7.495	1.666
II	18.341	0.863	5.648	2.059
III	17.576	0.659	4.743	2.317

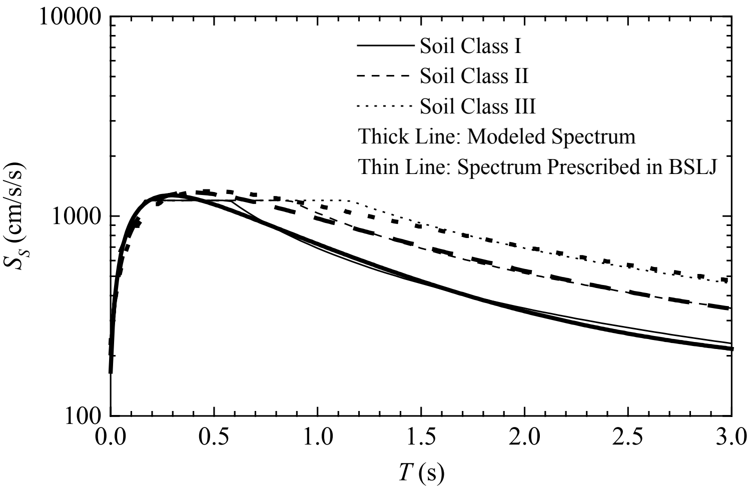
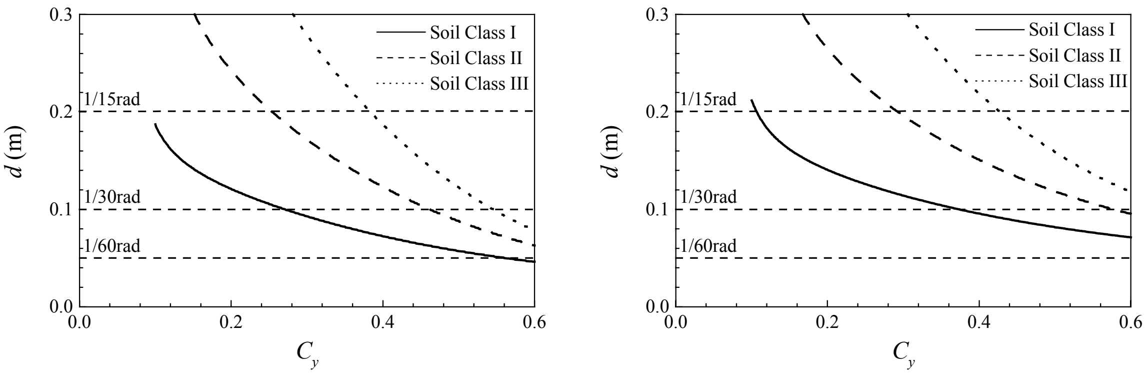


Figure 2.1. Acceleration Spectra

Fig. 2.2 show the maximum displacement responses, *d*, which are calculated by the Limit Strength Calculation Method, of the two types of structural models, the conventional house model (a) and the traditional house model (b), for the modeled spectra. The yield shear coefficient is C_y=0.1 to 0.6, the damping ratio h_0=0.05. The non-dimensional stiffness after the yielding to the initial stiffness is assumed to r_0=0.0. In this paper, these models and responses are called the "*Normal model*" and the "*Normal response*", respectively.



(a) Conventional House Model (b) Traditional House Model

Figure 2.2. "Normal Response" of "Normal Model"

3. STRENGTH INDEX, α

The strength index, α, for various seismic retrofits are defined by the next expression.

$$\alpha_i = \left(C_{yeq} - C_y\right)/C_y \tag{3.1}$$

where C_y is the yield shear coefficient of the structure before the retrofit. C_{yeq} is the yield shear coefficient of the normal model equivalent to the response after the retrofit. The subscript *i* of α represent the reduction of the mass (*M*), the increase of the viscous dumping (*D*) or the increase of the stiffness after the yielding (*R*).

3.1 Strength Index, α_M

The reduction of the mass, Δm, from the structure of an arbitrary mass, *m*, is equivalent to the retrofit by increasing the strength which corresponds to Δm. Then, α_M becomes

$$\alpha_M = \frac{\dfrac{Q_y}{m \cdot g - \Delta m \cdot g} - \dfrac{Q_y}{m \cdot g}}{\dfrac{Q_y}{m \cdot g}} = \frac{1}{1 - \dfrac{\Delta m}{m}} - 1 \tag{3.2}$$

where Q_y and *g* is the yield strength of the structure and the gravity acceleration.

3.2 Strength Index, α_D

Consider the retrofit by increasing of the viscous dumping, Δh, for the structure of an arbitrary C_y. The damping ratio after the retrofit is expressed as $h=h_0+\Delta h+h_{eq}$, where h_{eq} is the equivalent dumping ratio to the hysteretic dumping. C_{yeq} for this retrofit can be obtained from following procedures:

The response value on the acceleration response spectrum and the response value on the load-displacement relation are assumed to be S_A and Q_y, respectively. If these responses are truth, next expression will be obtained since the strength is equal to the seismic force.

$$m \cdot S_A / Q_y = 1 \tag{3.3}$$

The acceleration response which Δh is added to the normal model of Q_y is assumed to be S_{Ah}. The acceleration response of the normal model of Q_{eq} (=Q_y+ΔQ) is assumed to be S_{AQ}. If displacement responses of both models are equal, Eqn. 3.3 becomes

$$m \cdot S_{Ah} / Q_y = m \cdot S_{AQ} / Q_{eq} \tag{3.4}$$

therefore

$$Q_{eq} = \left(S_{AQ} / S_{Ah} \right) \cdot Q_y \tag{3.5}$$

If both sides of Eqn. 3.5 are divided by the weight, C_{yeq} is given by

$$C_{yeq} = \left(S_{AQ} / S_{Ah} \right) \cdot C_y \tag{3.6}$$

This C_{yeq} can be obtained from the following process: first obtain the displacement response of the model which the damping is added, next read C_y from Fig 2.2 which the response of the normal model is equal to the one of the dumped model.

Fig. 3.1 (a) and (b) show the relationship between Δh and α_D of the conventional and the traditional house models for the model spectrum of the soil class II, respectively. The dumping ratio and the yield shear coefficient are Δh=0.0 to 0.1 and C_y=0.1 to 0.5.

It is recognized from the figures that the Δh-α_D relation is seemed to be exponentiation in C_y=0.1 and linear in C_y=0.2 to 0.5. When C_y=0.1 and 0.2, C_y becomes smaller, α_D becomes larger. However, α_D is irrelevant to C_y when C_y=0.3 to 0.5. The seismic retrofit by increasing the dumping to traditional model is effective compared with a conventional one according to the house model. The effect of the seismic retrofit on stiff soil (soil class I) was high compared with the soft soil (soil class III) according to the soil class.

The regression formula of α_D for Δh is expressed as follows:

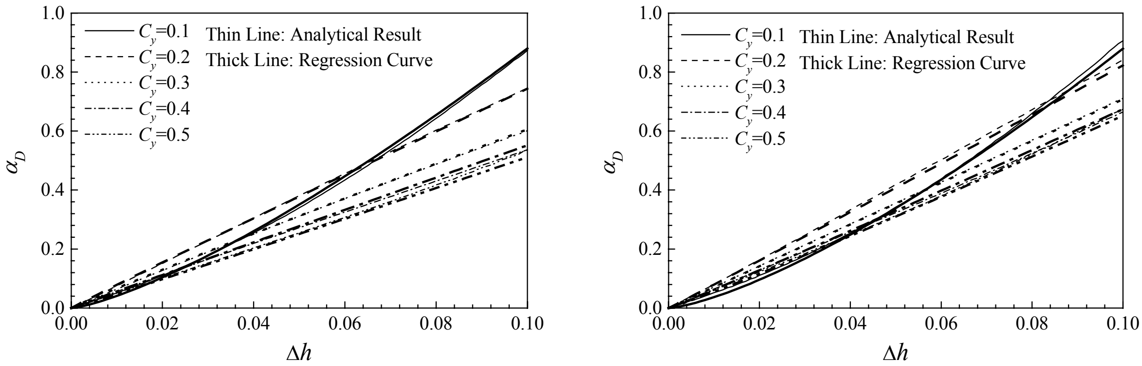
$$\alpha_D = \beta_D \cdot \Delta h^{\gamma_D} \tag{3.7}$$

where

$$\beta_D = {}_D b_1 \cdot C_y + {}_D b_2 \cdot e^{-C_y / {}_D b_3} + {}_D b_4 \tag{3.8}$$

$$\gamma_D = {}_D c_1 \cdot C_y + {}_D c_2 \cdot e^{-C_y / {}_D c_3} + {}_D c_4 \tag{3.9}$$

C_y in Eqn. 3.8 and 3.9 is the yield shear coefficient before the retrofit. The parameters are listed in Table 3.1 which are regressed by the least-squares method within $0.1 \le C_y \le 0.5$ and $0 \le \Delta h \le 0.1$. The regression curve obtained is shown by the thick line in Fig. 3.1 for the two houses.



(a) Conventional House Model (b) Traditional House Model

Figure 3.1. Strength Index, α_D (Soil Class II)

Table 3.1. Parameters of Eqn. 3.8 and 3.9

	Soil Class	β_D				γ_D			
		$_Db_1$	$_Db_2$	$_Db_3$	$_Db_4$	$_Dc_1$	$_Dc_2$	$_Dc_3$	$_Dc_4$
Conventional House Model	I	3.688	151.734	0.044	5.735	0.448	3.542	0.045	0.846
	II	1.244	97.456	0.051	4.832	0.412	3.059	0.053	0.822
	III	2.086	50.053	0.067	3.602	0.390	2.728	0.059	0.812
Traditional House Model	I	8.391	249.692	0.042	7.766	0.446	4.732	0.042	0.905
	II	4.754	103.520	0.052	5.306	0.407	3.455	0.050	0.868
	III	4.483	60.966	0.063	3.940	0.409	2.964	0.055	0.843

3.3 Strength Index, α_R

Consider the retrofit by increasing the stiffness after the yielding, r_0, for the structure of an arbitrary C_y. The shear coefficient of the normal model, which becomes the same displacement response, is assumed to C_{yeq}. α_R is obtained from the Eqn. 3.1.

The thin lines in Fig. 3.2 (a) and (b) show the relationship between C_y and α_R of the conventional and the traditional house models for the model spectrum of the soil class II, respectively. The stiffness is r_0=0 to 0.5, and C_y=0.1 to 0.5.

It is recognized form the figures that α_R increases as r_0 increases, and gradually gets closer to a given value. There is a little difference in α_R when $r_0 \geq 0.3$. Therefore, the seismic retrofit effect is not obtained even if r_0 is made large excessively. A difference of α_R clearly appears when C_y=0.1 to 0.3 according to C_y, but the difference is slight when C_y=0.3 to 0.5. Therefore, the retrofit by r_0 for high strength structure is not effective.

The regression formula of α_R for r_0 is expressed as follows:

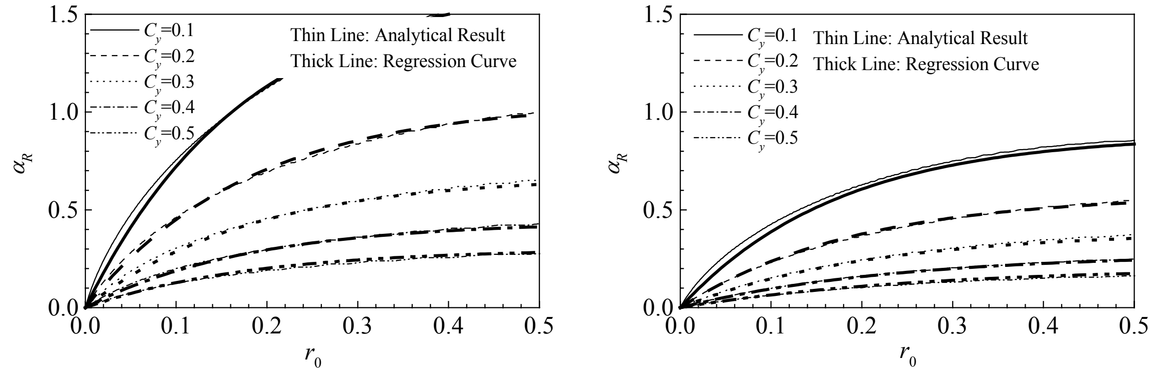
$$\alpha_R = \beta_R \cdot \left(1 - e^{-\gamma_R \cdot r_0}\right) \tag{3.10}$$

where

$$\beta_R = {}_Rb_1 \cdot e^{-C_y / {}_Rb_2} + {}_Rb_3 \tag{3.11}$$

$$\gamma_R = {}_R c_1 \cdot C_y + {}_R c_2 \tag{3.12}$$

C_y in Eqn. 3.11 and 3.12 is the yield shear coefficient before the retrofit. The parameters are listed in Table 3.2 which are regressed by the least-squares method within $0.1 \leq C_y \leq 0.5$ and $0 \leq r_0 \leq 0.5$. The regression obtained is shown by the thick line in Fig. 3.2 for the two houses.



(a) Conventional House Model (b) Traditional House Mode

Figure 3.2. Strength Index, α_R (Soil Class II)

Table 3.2. Parameters of Eqn. 3.11 and 3.12

	Soil Class	β_D			γ_D	
		${}_R b_1$	${}_R b_2$	${}_R b_3$	${}_R c_1$	${}_R c_2$
Conventional House Model	I	1.037	0.337	-0.048	-4.715	5.991
	II	2.623	0.200	0.086	-0.237	5.643
	III	4.009	0.165	0.164	1.253	6.698
Traditional House Model	I	0.727	0.078	0.051	-9.351	10.084
	II	1.295	0.202	0.097	-4.889	6.242
	III	2.411	0.185	0.127	-2.272	6.120

3.4 Examples of Combination of Various Retrofit

Here, we examine a combination technique of various retrofits for a structural model.

The structural models are assumed to two types of normal model, the conventional type with C_y=0.2 and the traditional one with C_y=0.15. The soil class II is chosen to the earthquake response spectrum. The target maximum story deformation angle responses are less than 1/30rad and 1/15rad for the conventional model and the traditional one. Required shear coefficient ${}_{req}C_y$ is known from Fig. 2.2: ${}_{req}C_y$ =0.55 and 0.28 for the conventional model and the traditional one.

If the increase of the strength, ΔC_y, the reduction of the mass, Δm, and the increase of the stiffness after the yielding, r_0, are combined for the seismic retrofit, the required stiffness ${}_{req}r_0$ for an arbitrary ΔC_y could be obtained form following procedure:

1) Assume the increase of the strength ΔC_y, and decide the total strength C_y+ΔC_y of the model. Since the retrofit by Δm can be considered as ΔC_y, the contributions of ΔC_y and Δm can be decided in the ΔC_y.
2) Calculate α_R by substitution C_{yeq}=${}_{req}C_y$ and C_y=C_y+ΔC_y into Eqn. 3.1.

3) Calculate Eqn 3.11 and 3.12, and solve ${}_{req}r_0$ for Eqn. 3.10.

Fig. 3.3 shows the relationship between ΔC_y and r_0 obtained from the above-mentioned procedure. It is recognized from the figure that r_0 is irrelevant to ΔC_y for both the traditional and the traditional models when about r_0>0.3. Therefore, if ΔC_y of a constant is not given, the effect of seismic retrofit by r_0 could not be expected. The stiffness should be $r_0 \leq 0.3$ to obtain the retrofit effect, and the required strengths are about $\Delta C_y \geq 0.21$ and 0.04 for the conventional model and the traditional one.

If ΔC_y, Δm, r_0, and the increase of the viscous damping, Δh, are combined, the required damping Δh_{req} for arbitrary ΔC_y, Δm and r_0 is obtained form following procedure. The procedures after 2) are shown since the procedure 1) is the same as the above-mentioned one.

2) Set r_0 and calculate α_R.
3) Calculate α_D by substitution $C_{yeq}={}_{req}C_y$ and $C_y=(1+\alpha_R)\cdot(C_y+\Delta C_y)$ into Eqn. 3.1.
4) Calculate Eqn. 3.8 and 3.9, and solve Δh_{req} for Eqn. 3.7.

Fig. 3.4 shows the relationship between ΔC_y and Δh_{req} obtained from the above-mentioned procedure. The stiffness is assumed to r_0=0.0, 0.1, 0.2, and 0.3 which are taken into consideration of the result of Fig. 3.3. It is qualitatively recognized that the retrofit effect by Δh is invariably expected for both the conventional and the traditional models, contrary to the case of the retrofit by r_0. The required Δh_{req} for r_0=0.2 and 0.3 are less than half of one for r_0=0.0.

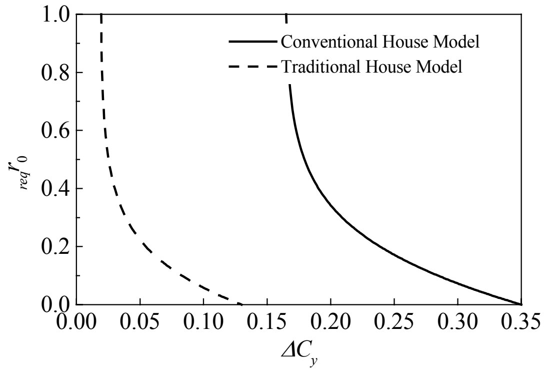


Figure 3.3. An Example of Calculation of ${}_{req}r_0$

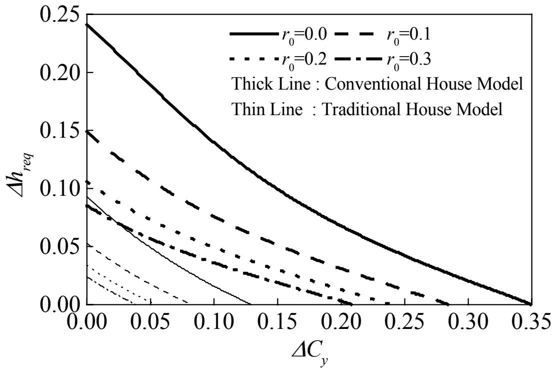


Figure 3.4. An Example of Calculation of Δh_{req}

4. A REINFOECING ELEMENT BY INCREASE OF STIFNESS AFTER YIELDING

From the results above mentioned, the retrofit by increasing the stiffness after yielding is effective. Here, we examine a reinforcing element and its restoring force characteristics form analytical viewpoint.

Fig. 4.1 shows the restoring force characteristics of the wooden frame called "*Ladder type frame*". Note the hysteretic process of this figure. A clear slip phenomenon is observed. If apply its hysteretic process to a reinforcing element, the element which increase the stiffness after the yielding could be realized, that is, the element which works only when the main earthquake-resisting elements is yielding could be realized. Referring to this restoring force characteristics, non dimensional restoring force Φ_h of the hardening type is represented as follows:

$$
\Phi_h = \begin{cases} -1 & ;\phi < -R_2 \\ \eta(\phi + R_2)^{\nu} - 1 & ;-R_2 \le \phi < -(R_1 + R_2)/2 \\ -\eta(\phi + R_1)^{\nu} & ;-(R_1 + R_2)/2 \le \phi < -R_1 \\ 0 & ;-R_1 \le \phi < -R_1 \\ -\eta(\phi - R_1)^{\nu} & ;-R_1 \le \phi < (R_1 + R_2)/2 \\ \eta(\phi - R_2)^{\nu} + 1 & ;-(R_1 + R_2)/2 \le \phi < -R_1 \\ 1 & ;\phi > R_2 \end{cases} \tag{4.1}
$$

where

$$
\eta = 2^{\nu-1} \big/ (R_2 - R_1)^{\nu} \tag{4.2}
$$

$$
\nu = 2n \tag{4.3}
$$

ϕ is the story deformation angle, R_1 and R_2 the angle of the beginning and the end of the hardening, respectively. n a positive integer related to the hardening. The scheme of this equation is shown in Fig. 4.2.

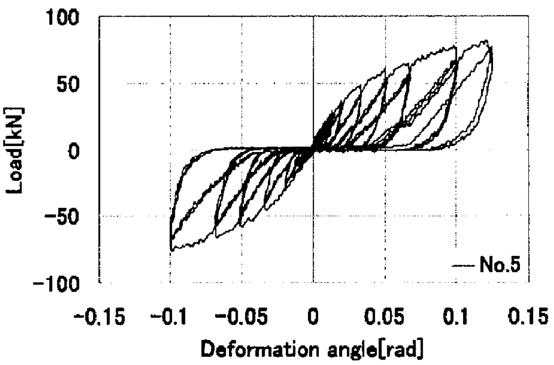


Figure 4.1. Restoring Force Characteristics of Ladder Type Frame

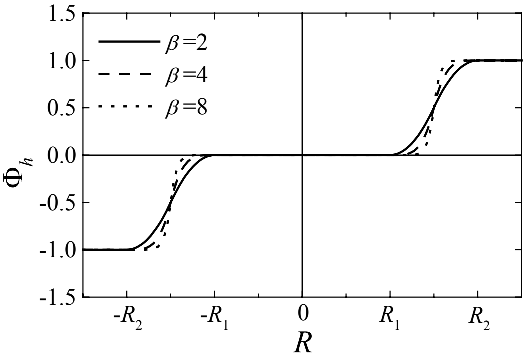
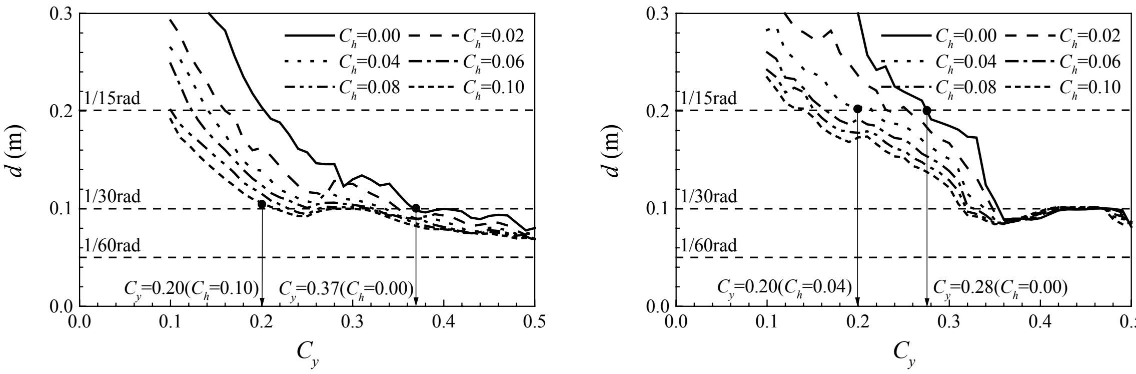


Figure 4.2. Non Dimensional Hardening Type Restoring Force Characteristics



(a) Conventional House Model

(b) Traditional House Model

Figure 4.3. Maximum Relative Story Displacement Response of Model Introducing Hardening Element

Fig. 4.3 (a) and (b) show the maximum relative story displacement responses of the time history response analysis of the models which the hardening type restoring force characteristic is introduced. The BCJ L2 wave is chosen to the input earthquake motion. As for the hysteresis rule before retrofit, the combination characteristics is used which consists of the bi-linear type and the slip one. Its combination rate is 0.4:0.6. The last stiffness r_0=0.0 to 0.1. The parameters which determine the shape of the hardening (R_1, R_2)=(1/120rad, 1/60rad) and (1/60rad, 1/30rad) for the conventional model and the traditional one. n=2 for both the models. C_h in the figure is the shear coefficient of the maximum strength of reinforcing element, C_h=0.0 to 0.1.

It is recognized from Fig. (a) that C_y=0.37 is required for which the response of the conventional model of C_y=0.2 does not exceed the criteria of 1/30rad without introducing the hardening type reinforcing element. That is, the strength of ΔC_y=0.17(=0.37-0.2) is necessary. On the other hand, in case of which the strength is not increased, if the hardening element with C_h=0.1 is introduced, the response would not exceed the criteria. Therefore, the hardening type element is effective compared with the normal retrofit by increasing the strength. From Fig. (b), C_y=0.28 is required for which the response of the traditional model of C_y=0.2 does not exceed the criteria of 1/15rad without introducing the hardening type reinforcing element. On the other hand, in case of which the strength is not increased, if the hardening element with C_h=0.04 is introduced, the response would not exceed the criteria.

5. CONCLUSIONS

In this paper, we introduced a new strength index into the seismic retrofit technique for the existing wooden houses. First, we formulated the index and decided its parameters agreed with the earthquake response spectra. Next, the application of the formulation was discussed. Furthermore, in order to realize the seismic retrofit, we proposed a reinforcing element, which was the hardening type in the restoring force characteristics; i.e., the stiffness increases after the yielding. The results obtained are concluded as follows:

1) When the horizontal load-carrying capacity and the displacement response before the seismic retrofit are known, using the index, the effect of seismic retrofit could be easily evaluated.

2) Reducing the mass of house is equivalent to increasing the bearing wall.

3) When the horizontal load-carrying capacity of the house is low, the effect of seismic retrofit by increasing the viscous damping is affected by the slight difference in the capacity.

4) In order to obtain the effect of the seismic retrofit, the stiffness after the yielding must be $r_0 \leq 0.3$.

5) It is very effective for the seismic retrofit to introduce the hardening type of the restoring force characteristics into the earthquake resisting element.

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