Progressive Construction of Hysteresis Models for Woodframe Houses with Visco-Elastic Structural Control Devices

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SUMMARY

This paper presents a progressive method to construct restoring force characteristics of woodframe houses based on hysteretic characteristics of individual element. The individual characteristics of the elements such as woodframe of columns and beams, braces and vibration control devices are determined by a series of pseudo dynamic tests conducted for three specimens. The isolated characteristics are expressed by the Bouc-Wen model. The applicability of the proposed composition method is validated through a simulation analysis for shaking table tests conducted for a woodframe specimen with visco-elastic structural control devices.

1. Introduction

In assessing structural safety of wooden structures by seismic response analyses, it becomes important to express the nonlinear characteristics of structures appropriately. Woodframe houses are composed of various elements such as beam-column, braces, shear wall panels, structural control devices and so on. It is desirable to construct the overall nonlinear characteristics of the structures based on the hysteretic characteristics of the individual elements. Though some hysteretic models applicable to wooden houses have been proposed, the method to construct systematically the hysteretic characteristics based on those of individual elements including visco-elastic structural control devices has not been established. This paper describes a method to construct nonlinear characteristics of woodframe houses with visco-elastic structural control devices on the basis of hysteretic characteristic of each element extracted from pseudo-dynamic tests. The applicability of the composition method is validated by a simulation analysis for experimental results conducted by a shaking table test.

2. Extraction of Hysteretic Characteristics of Elements

2.1 Pseudo-Dynamic Tests of Wooden Frames

A series of pseudo-dynamic tests of woodframes with and without braces or visco-elastic structural control devices have been conducted to extract the hysteresis characteristics of elements composing woodframe houses. Three specimens and the corresponding names are shown in Fig. 1. The specimen GVA is a woodframe structure with diamond-shaped vibration control devices, each of which has visco-elastic (VE) dampers at the top and bottom of the devices. Deformation of the VE damper is limited to 15 mm, beyond of which wooden braces withstand the lateral force exerted on GVA. Dimensions of the members of specimens are shown in Table 1.

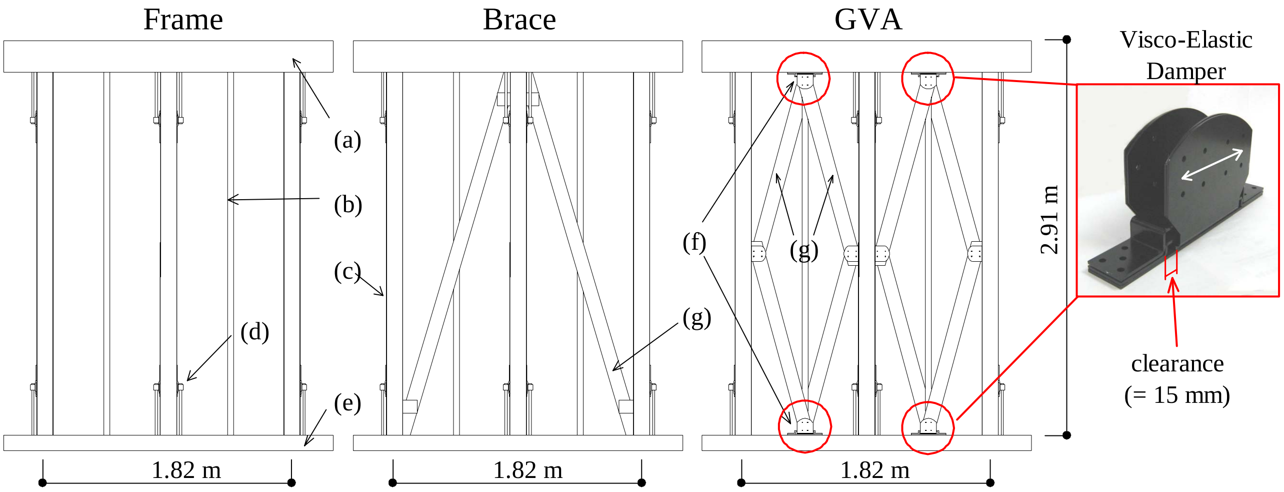

Fig. 1 Elevation of Specimens

Table 1 Dimension of Members

(a)	Cross Beam : 210mm × 105mm
(b)	Stud : 45mm × 30mm
(c)	Column : 105mm × 105mm
(d)	Beam-Column Joint Hardware
(e)	Sill Beam : 105mm × 105mm
(f)	Visco-Elastic Damper (Visco-Elastic Material = 120mm × 89mm × 5mm × 2sheets)
(g)	Brace : 45mm × 90mm

Table 2 Combination of Excitation Amplitude and Frequency

Order of Excitation	1	2	3	4	5
Interstory Deformation Angle [rad.]	1/240	1/120	1/60	1/30	1/15
Frequency of Exc. [Hz]	2.0	1.0	0.5	0.25	0.125

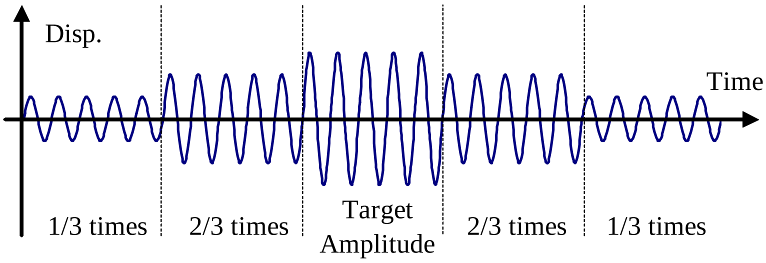

Fig. 2 Time History of Excitation

Pseudo-dynamic tests were performed by a sinusoidal forced-displacement test with changing the amplitudes and the frequencies. The combination of excitation amplitude and frequency is shown in Table 2. Forced-displacement time history of the excitation is shown in Fig. 2. The lateral load was given by actuator and displacements were observed by dial gauges and laser meters. The averaged results of 2 to 4 cycles for each stage of excitation are used in the following analyses.

2.2 Extraction of Hysteretic Characteristics of Individual Elements

On the basis of the superposition law of stiffness, which has been confirmed by authors (Sato et. al 2006 [1]), the hysteretic characteristics of respective elements may be extracted by the pseudo-dynamic tests carried out for specimens shown in Fig.1. The extracted hysteretic characteristics of elements of woodframe, brace and GVA are shown in Fig. 3 for different interstory angles.

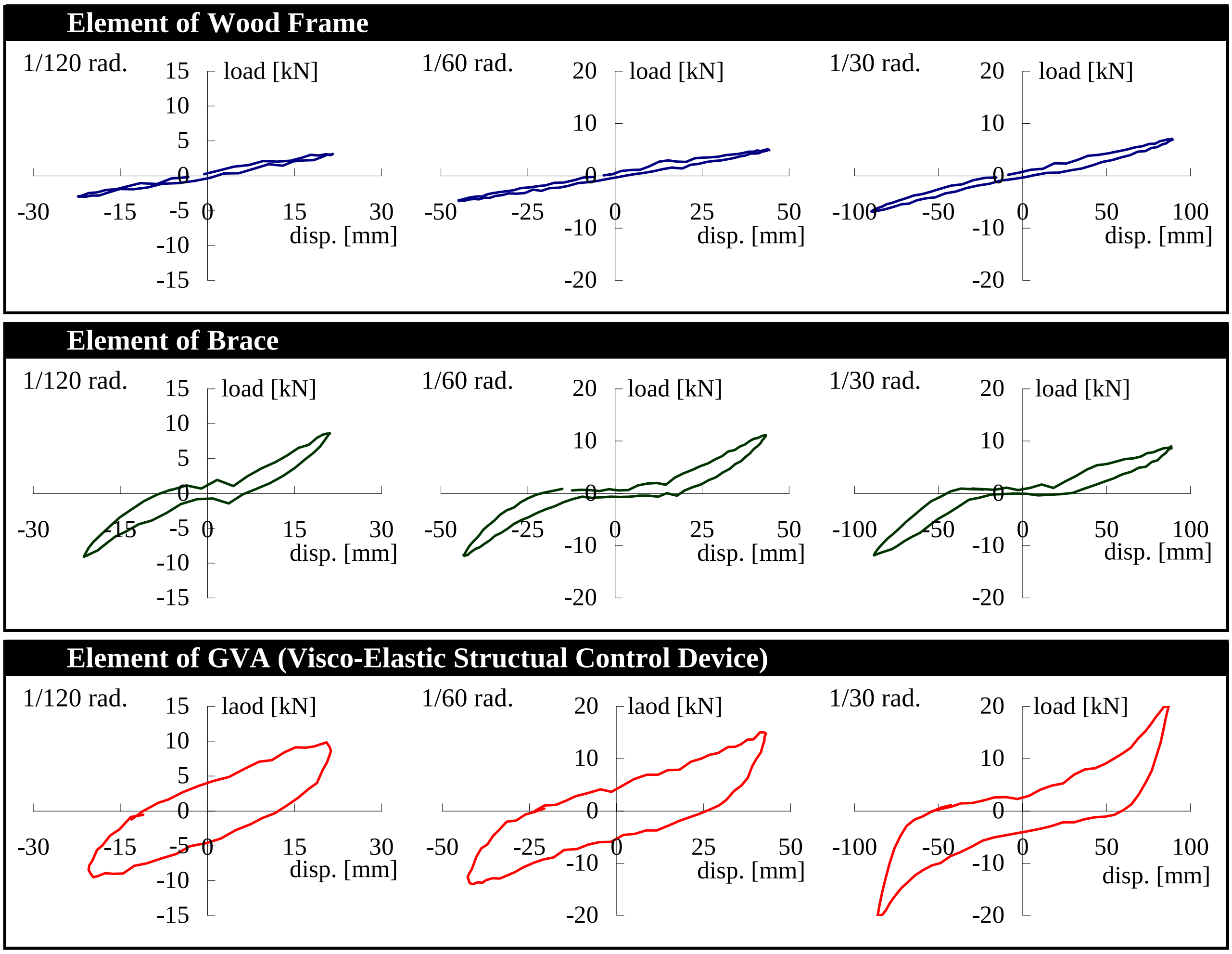

Fig. 3 Hysteretic Characteristics of Individual Elements

3. Construction of Hysteretic Models

3.1 Outline of Modeling of Hysteretic Model

Hysteretic characteristics of the elements tend to show a strong nonlinearity of spindle-shaped even for small deformation, and pinching behavior with increasing of deformation as shown in Fig. 3. It is intended, for convenience of response analyses, to express analytically the nonlinear hysteresis by a combination of spindle-shaped and strong slip behavior with use of Bouc-Wen model (Wen 1976 [2]) as shown in Fig. 4 (Sato et. al 2007 [3]). The analytical models adopted in this paper are shown in Eqs (1) and (2).

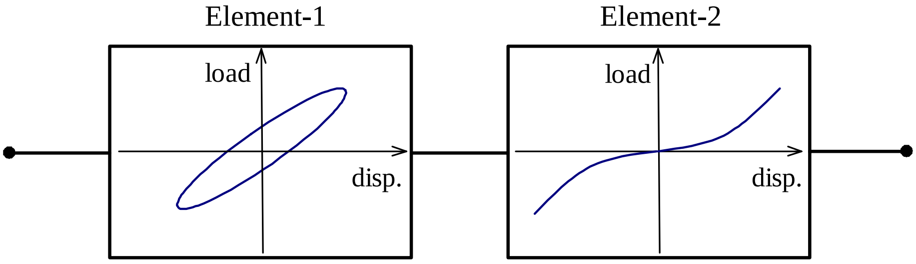

Fig. 4 Mechanical Model for Woodframe and Brace Elements

$$\text{Element}-1 : \dot{Z} = A_1\dot{x} - \beta_1\left|\dot{x}\right|Z \tag{1}$$

$$\text{Element}-2 : \dot{Z} = A_2\dot{x} - \gamma_2\dot{x}\left|Z\right| \tag{2}$$

where Z is the lateral load, x is interstory deformation, and A_1, β_1, A_2, γ_2 are parameters expressing the hysteresis shapes. Explicit expressions for Z can be obtained by solving the differential equations.

3.2 Method to Identify Parameters of Hysteresis Model

The parameters of Eqs (1) and (2) can be determined on basis of the experimental results for the respective elements. For Element-1 shown in Fig. 4, the parameters are determined so as to make the dissipation hysteresis energy correspond to the analytical model. The schematic concept is illustrated in Fig. 5, in which Δx_i is the width of a loop corresponding to Z_i.

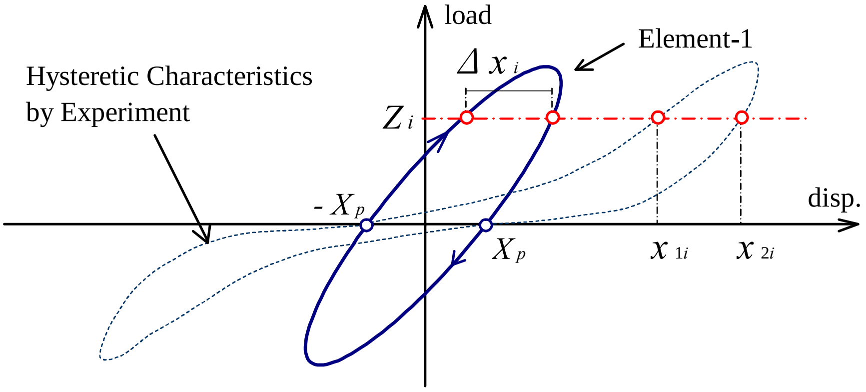

Fig. 5 Extraction of Element-1 from Experimental loop

With use of the solution of Eq. (1), the width may be given by the following equation.

$$\Delta x_i = 2X_p + \frac{1}{\beta_1}\log\left(1 - \frac{\beta_1^2 Z_i^2}{A_1^2}\right) \tag{3}$$

The parameter A_1 and β_1 in Eq. (3) are determined so as to minimize a functional given by

$$f\left(A_1, \beta_1, X_p\right) = \sum_{i=1}^{n} w_i\left(x_{2i} - x_{1i} - \Delta x_i\right)^2 \tag{4}$$

in which w_i is weighting factors. The parameters of Element-2 shown in Fig. 4 can be determined based on the hysteresis loop evaluated by subtracting the loop of Element-1 from the experimental loop. The detail may be found elsewhere (Sato et. al 2007 [3]).

3.3 Modeling of Visco-Elastic Structural Control Device

The hysteretic characteristics of the GVA element shown in Fig. 3 include both the characteristics of wooden braces and those of VE dampers. By decomposing the hysteretic characteristics of GVA into those of the composition members, the performance of the device GVA may be definitely evaluated. It is reasonable to assume that the VE damper and the braces are subjected to the same force. Thus, the mechanical model of the structural control device can be expressed by a series connection of these hysteresis as shown in Fig. 6.

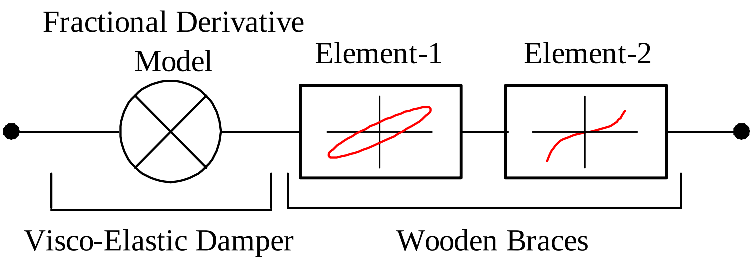

Fig. 6 Hysteretic Model of Visco-Elastic Structural Control Device

As for the VE material, we try to express the characteristics theoretically. Following the papers by Kasai et. al (Kasai 2001 [4] , 2002 [5]), a fractional derivative model for the constitutive equation shown in Eq. (5) is adopted in this paper.

$$\dot{\tau} + a D^{\alpha}\tau = G\left(\dot{\gamma} + b D^{\alpha}\gamma\right) \qquad (5)$$

where τ is shear stress, γ is shear strain, D^{α} is α-th fractional derivative operator ($= d^{\alpha}/dt^{\alpha}$) and a, b and G are parameters to be determined according to the change of temperature, frequency and stress level generated in the VE materials. It may be shown that hysteretic characteristics of the VE damper shown in Fig. 6 can be expressed finally as follows. The detail will be found in a different paper (Sato et. al 2008 [6]).

$$\dot{Z} = C_1 \dot{x}_d + C_2 x_d + C_3 \qquad (6)$$

where Z is the lateral load applying on the damper and x_d is the deformation of the VE damper, and C_1, C_2 and C_3 are the coefficient determined by the constitutive equation shown in Eq. (5).

Based on the hysteretic characteristics obtained by Eq. (6), the characteristics of wooden braces can be isolated by subtracting the hysteresis loop of VE damper from that of GVA shown in Fig. 3. The resolved hysteresis loops are shown in Fig. 7 for interstory displacement angles 1/120 rad and 1/30 rad. In the results of VE damper, due to the effect of stoppers a spike-like hardening is recognized in the result of 1/30rad.

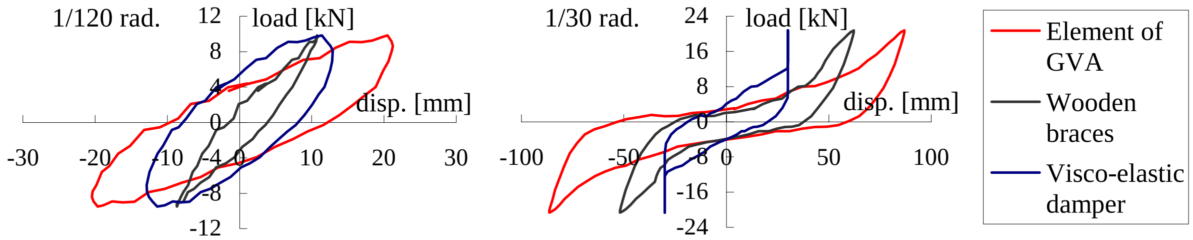

Fig. 7 Resolved Hysteresis loops of Wooden Braces and Visco-Elastic Damper

4. Seismic Simulation Analyses of Shaking-Table Tests

4.1 Outline of Experiment

The shacking-table tests were conducted for one-story woodframe structure shown in Fig. 8 (Sato et. al 2007 [7]). The specimen has four pairs of double braces and two structural control devices in the direction of excitation. On the top of the specimen steel plates of approximately 40kN of weight was mounted, which is equivalent to the weight of upper story. Regarding an input earthquake motion to the shaking table, the acceleration record of JMA-Kobe of *Hyogoken-Nanbu Earthquake* which was scaled to 25 cm/sec and 50 cm/sec of the maximum velocity was applied. The observation points of the response are shown in Fig. 8.

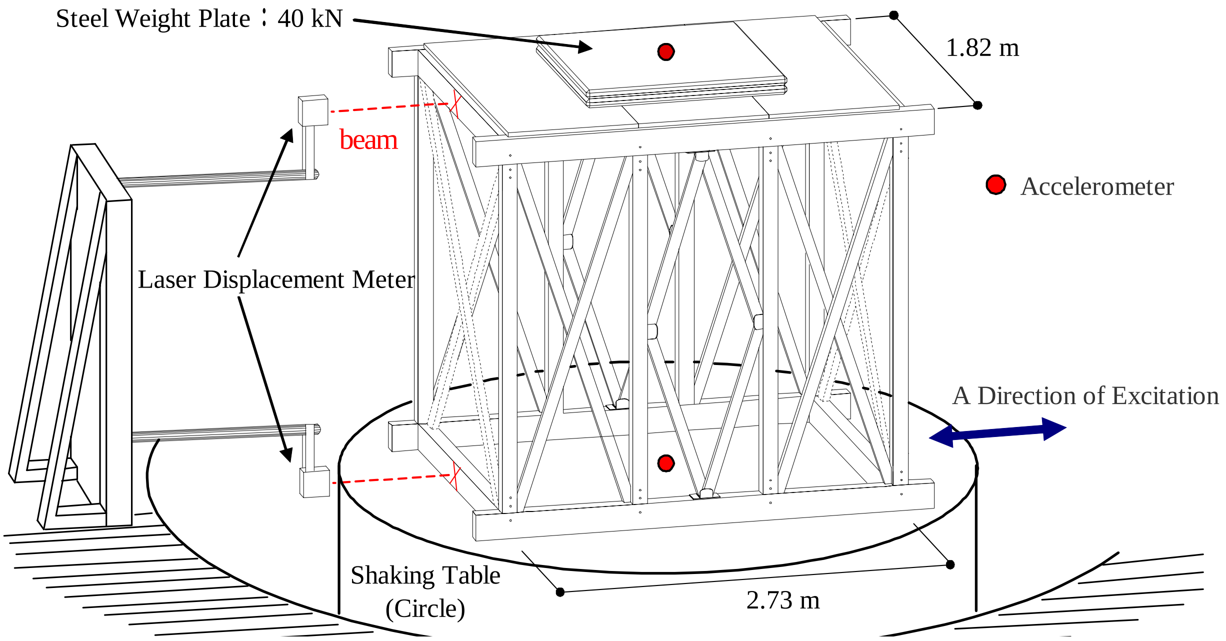

Fig. 8 Outline of Shaking-Table Test and Observation System

4.2 Construction of Hysteretic Characteristics and Response Analyses

Hysteretic characteristic of this specimen can be constructed by adding the individual characteristics of elements as shown in Fig. 9 In addition to the hysteresis damping of each element, a certain viscous damping is introduced in the mechanical model.

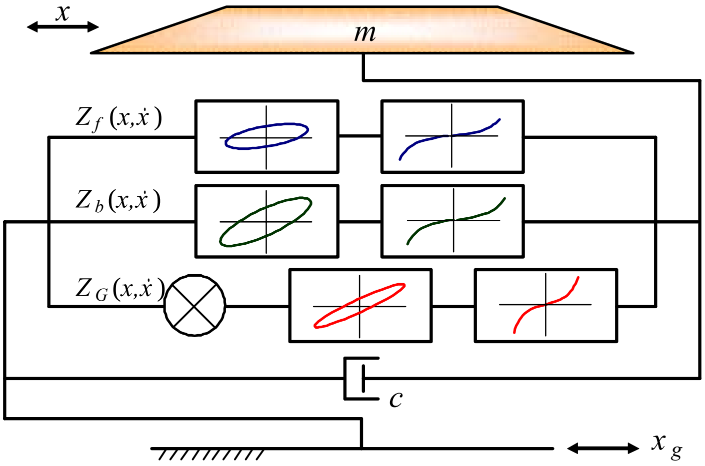

Fig. 9 Mechanical Model for the Simulation Analyses

For the system shown in Fig. 9, the equation of motion can be written as follows:

$$\ddot{x}+\frac{c}{m}\dot{x}+\frac{1}{m}\sum Z_i\left(x,\dot{x}\right)=-\ddot{x}_g \tag{7}$$

in which Z_i ($i = f, b, G$) are restoring forces of the respective elements of frame, brace and GVA. For the frame and brace, the restoring forces may be expressed by Eq. (8) with consideration of Eqs (1) and (2).

$$\dot{Z}_i = K_i \cdot \dot{x} = \frac{K_{1i} \cdot K_{2i}}{K_{1i} + K_{2i}} \cdot \dot{x} \qquad (8)$$

where $$K_{1i} = \frac{dZ}{dx_1} = A_{1i} - \beta_{1i} \frac{|\dot{x}_1|}{\dot{x}_1} Z_i \ , \ K_{2i} = \frac{dZ}{dx_2} = A_{2i} - \gamma_{2i} |Z_i| \qquad (9)$$

As for GVA, the restoring force Z_G may be shown to be expressed formally as follows.

$$\dot{Z}_G = \frac{K_{Gb} \cdot K_{Gd}}{K_{Gb} + K_{Gd}} \cdot \dot{x} \qquad (10)$$

where K_{Gb} is the equivalent stiffness of wooden braces of the GVA element and K_{Gd} is the stiffness of VE damper. On the basis of Eq. (6), K_{Gd} may be expressed by

$$K_{Gd} = C_1 + C_2 \frac{x_d}{\dot{x}_d} + C_3 \frac{1}{\dot{x}_d} \qquad (11)$$

In numerical calculation of the equation of motion, the Runge-Kutta method was made use of.

4.3 Verification of Seismic Simulation Analyses

The method for composition of the hysteretic characteristics of woodframe houses installed structural control device was validated by comparing the numerically evaluated and the shaking-table test results.

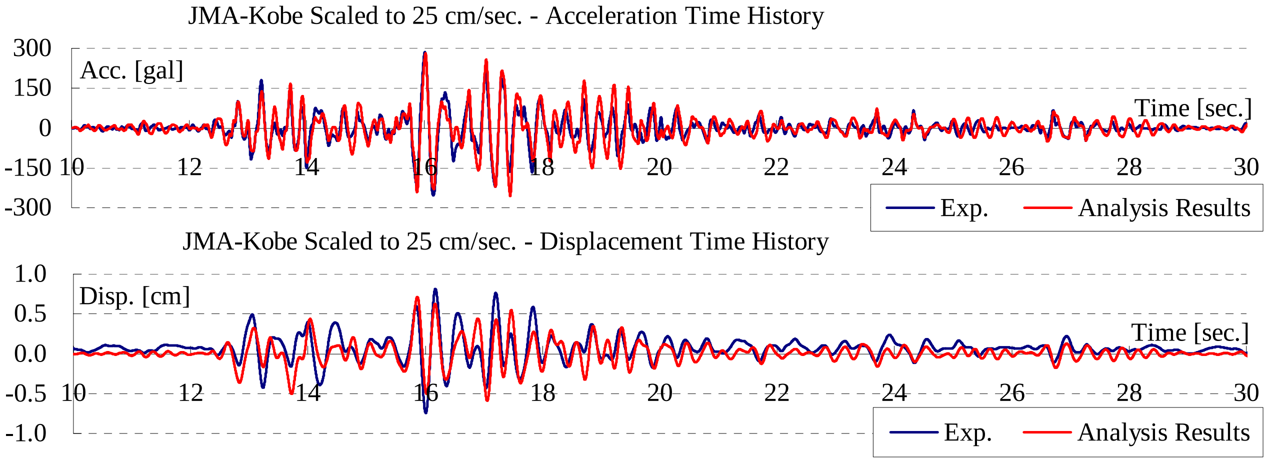

Fig. 10 Comparison between Analysis and Experimental Results (max. vel. 25 cm/sec.)

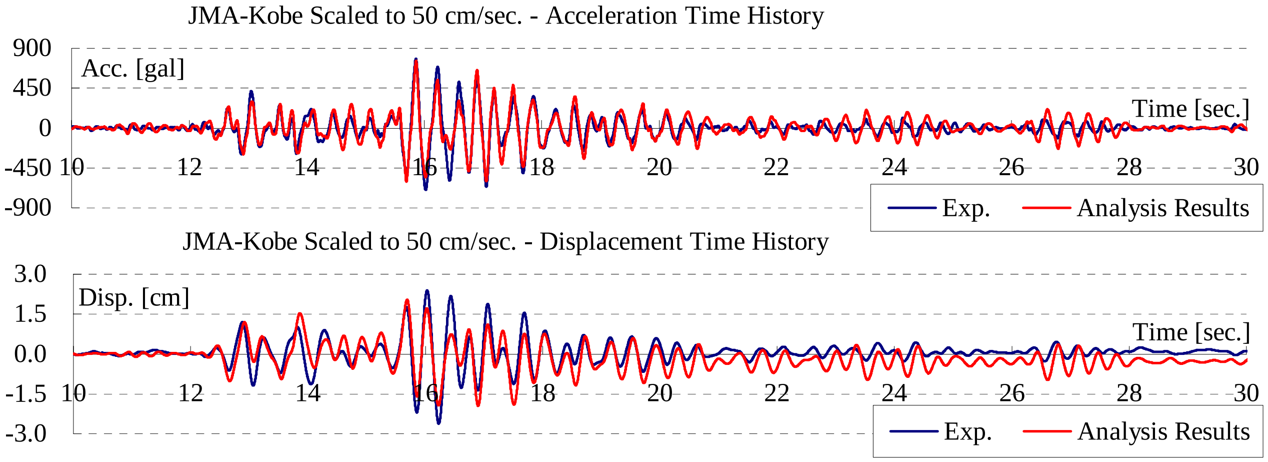

Fig. 11 Comparison between Analysis and Experimental Results (max. vel. 50 cm/sec.)

The compared results of acceleration and displacement responses are shown in Fig. 10 for a maximum input of a velocity scaled to 25 cm/sec. We will notice fairly good agreement between the two results. In Fig. 11, the comparisons of the results are shown for a maximum input velocity scaled to 50 cm/sec.

5. Conclusion

In this study, a method is proposed to compose the hysteretic characteristics of woodframe houses including visco-elastic structural control devices on the basis of the respective elements which are determined by a series of pseudo dynamic tests. The effectiveness and applicability of the method are confirmed by comparing the analytically evaluated responses with experimental results conducted with use of a shaking-table. The advantage of the proposal method may be summarized as having the capability to construct restoring force characteristics of varied woodframe houses which are composed of the elements such as beam-column frames, braces and vibration control devices with VE dampers.

Acknowledgement

The study was carried out under the support of KANAI co., Ltd, Sumitomo 3M Ltd, IMA co., Ltd and HARADA Logitex co., Ltd, Housing Structure Research Institute co., Ltd and Electric Power Development co., Ltd, Chigasaki Research Institute. The collaboration for the tests is gratefully acknowledged.

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