SEISMIC PERFORMANCE EVALUATION METHOD FOR A BUILDING WITH CENTER CORE REINFORCED CONCRETE WALLS AND EXTERIOR STEEL FLAME

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SUMMARY

The Hybrid Wall System (HWS) building composed of center core reinforced concrete walls and exterior steel flame has the open space around the center core walls that is architecturally desirable. It is necessary to develop design methodologies for the HWS building that the coupled shear walls withstand the most of lateral load and expect the most energy dissipation at the coupling beams and at wall foots. The seismic performance evaluation method for HWS building proposed, in this paper is utilizing the HWS building seismic behavior that the primary vibration mode of the HWS building doesn't change from elastic region to plastic region, and its overall behaviour can be represented by the relationship of shear coefficient v.s. displacement on the equivalent single-degree-of-freedom system (the capacity curve). The demand performance is indicated as the response spectrum considering hysteresis damping effect of the building in each drift level (the demand curve). The overall seismic performance for HWS building can be evaluated as the crossing point of the capacity curve and the demand curve. And the seismic performance of the 1/3-scale 12-story coupled shear wall test specimen is evaluated by this method for example.

INTRODUCTION

The U.S.- Japan cooperative structural research project on composite and hybrid structures have conducted from 1994 for 5-years. A building with center core reinforced concrete walls and exterior steel flame was selected as a target building for Hybrid Wall System (HWS, in Figure 1) that is one of four composite and hybrid structure systems, i.e., Concrete Filled Tube Column System (CFT), Reinforced Concrete Column and Steel Beam System (RCS), Research for Innovation (RFI) [Yamanouchi et al, 1994]. The HWS building has the open space around the center core wall that is architecturally desirable. The center core wall is divided into several walls that are linked together by coupling beams and forms coupled shear walls. The coupled shear walls are the primary lateral load-resisting element in the HWS building. Flange part of each wall in the coupled shear walls can reduce seismic compressive stresses, and hence improve the overall seismic performance of the coupled shear wall. The coupling beams can be designed to absorb the most of the seismic energy as well as the wall foots. It was confirmed that the HWS building had an excellent seismic performance from seismic test on 1/3 scale 12-story coupled shear wall with flange walls (hereafter 12-story test) [Teshigawara et al, 1998]. Its hysteresis characteristic was stable until building drift angle of *1/67* (i.e., deflection angle at the 12^{th} floor). The coupling beams and the wall foots absorbed the most of the seismic energy. Their deformation capacity was at the overall building drift of *1/25*.

At present, the design methodologies of the buildings with shear walls are prepared sufficiently in Japan, and the HWS building isn't designed rationally. It is necessary to develop design methodologies that are suitably evaluated seismic performance of the HWS building.

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The HWS building will be expected that the characteristics under earthquake motions be dominated by the vibration mode of the coupled shear walls. Its primary vibration mode doesn't change from elastic region to plastic region, and its overall behavior can be represented by the relationship of shear coefficient v.s. displacement on the equivalent single-degree-of-freedom (SDOF) system (in Figure 2). This is designated as the capacity curve. The demand performance is indicated as the response spectrum considering hysteresis damping effect of the building in each drift level. This is designated as the demand curve. The overall seismic performance for HWS building can be evaluated by comparing the capacity curve and the demand curve (in Figure 3).

In this paper, the seismic performance evaluation method for HWS building is proposed, and the seismic performance of the 1/3-scale 12-story coupled shear wall test specimen is evaluated by this method for example.

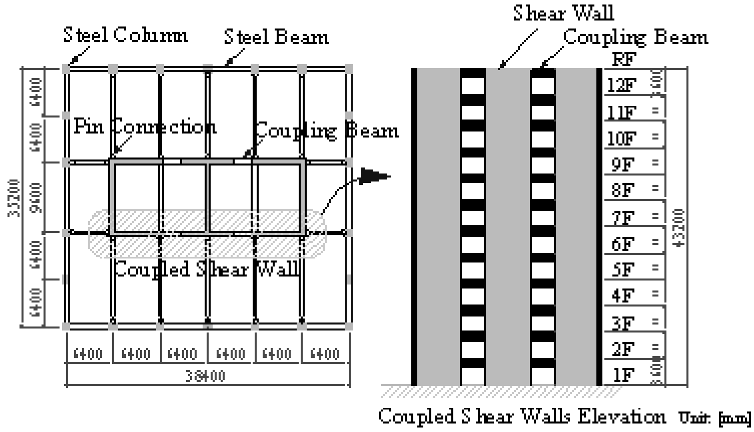


Figure 1: Plan of Prototype Building.

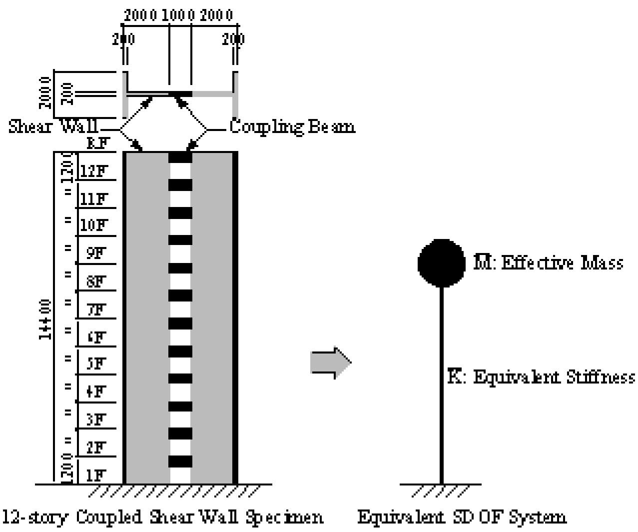


Figure 2: 12-story Coupled Shear Wall Test Specimen and Equivalent SDOF System.

SEISMIC PERFORMANCE EVALUATION METHOD

The general idea of the seismic performance evaluation method for HWS building is shown in figure 3. Its overall structural characteristic is represented by capacity curve that is relationship of shear coefficient v.s. displacement as the equivalent SDOF system. Demand performance is represented by demand curve that is relationship of acceleration (Sa) and displacement (Sd) response spectrum considering hysteresis damping effect of the building in each drift level. The overall seismic performance for HWS building can be evaluated as the crossing point of the capacity curve and the demand curve. Demand curve is provided as the line connecting the points on the response spectrum with each damping factor and equivalent period.

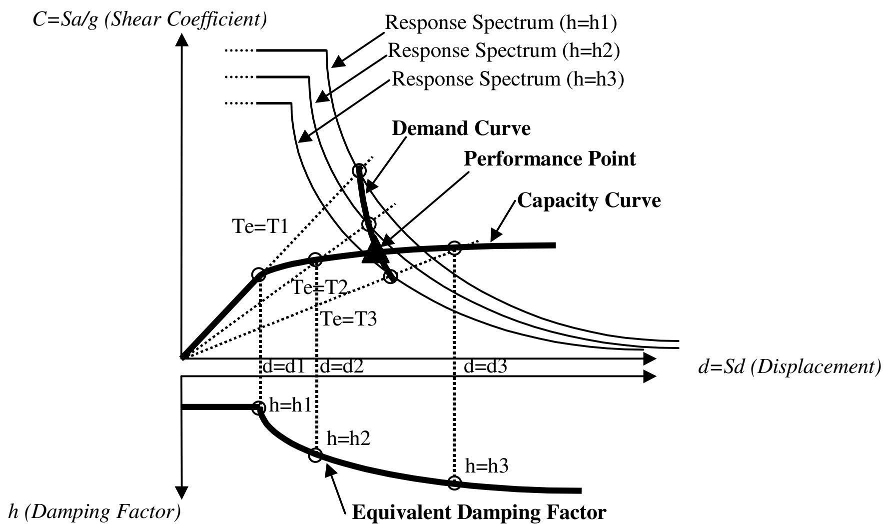


Figure 3: The General Idea of Seismic Performance Evaluation Method.

PROCEDURES OF SEISMIC PERFORMANCE EVALUATION METHOD AND APPLICATION

Capacity Curve

The seismic performance of HWS building is dominated by the vibration mode of the coupled shear wall. In figure 4, the deformation mode at the 12-story test is shown at each drift. According to 12-story test, its vibration characteristic is predominant by the 1st mode, and its vibration mode doesn't change from elastic region to plastic region.

When HWS building vibrates at 1st mode, displacement at ith-story is defined with equation (1).

$${_1d_i} = {_1\beta} \cdot {_1u_i} \cdot Sd \qquad \text{----------(1)}$$

where, ${_1d_i}$: *Displacement at ith-story*
${_1\beta}$: *Modal Participation Factor for 1st mode*
${_1u_i}$: *Amplitude at ith-story for 1st mode*
Sd : *Displacement Response of SDOF system*

Representative displacement on capacity curve which is coordinate with displacement response of SDOF system is the displacement at the height where participation function for 1st mode is equal to *1.0* (${_1\beta} \cdot {_1u} = 1.0$; i.e., equivalent height).

When the external forces with 1st mode distribution along the height are applied to HWS building, external force at ith-story is defined by the equation (2).

$$P_i = {_1\beta} \cdot {_1u_i} \cdot m_i \cdot Sa \qquad \text{----------(2)}$$

where, P_i *External Force at ith-story*
m_i : *Mass at ith-story*
Sa : *Acceleration Response of SDOF system*

Base shear force is defined by the equation (3).

$$Qb = \sum_{i=1}^{n} P_i = {_1\beta}\{{_1u}\}^T [M]\{1\} Sa = {_1\overline{M}} \cdot Sa \qquad \text{----------(3)}$$

where, Qb : *Base Shear Force*
$[M]$: *Mass Matrix*
${_1\overline{M}}$: *Effective Mass for 1st mode* $\left(= {_1\beta}\{{_1u}\}^T [M]\{{_1u}\} = {_1\beta}\{{_1u}\}^T [M]\{1\}\right)$

Representative shear coefficient on capacity curve which is coordinate with shear coefficient of SDOF system is defined by the equation (4).

$$C = {Sa}/{g} = {Qb}/\left({}_1\overline{M} \cdot g\right) \qquad \text{----------(4)}$$

where, g *Gravity Acceleration*

Relationship of shear coefficient v.s. displacement and capacity curve of equivalent SDOF system of 12-story test specimen are calculated from the above equations, and those are shown in figure 5. Representative displacement is displacement at 9th floor (i.e., ${}_1\beta \cdot {}_1u_9 = 1.0$ from figure 4), and representative shear coefficient is base shear force divided by equivalent mass for 1st mode and gravity acceleration. Equivalent mass for 1st mode on 12-story test at each drift is shown in table 1. Its vibration mode and its equivalent mass don't change almost from linear region to nonlinear region. Therefore, it can be considered that the above equations are proper in nonlinear region as well as linear region.

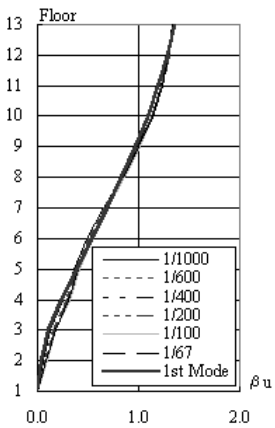


Figure 4: Deformation Mode (12-story test).

Table 1: Effective Mass. (12-story test)

Drift Angle	Effective Mass	${}_1\overline{M}/M$
R(rad)	${}_1\overline{M}$ N·sec²/mm	
1/1000	239.2	0.727
1/600	243.2	0.738
1/400	245.6	0.746
1/200	245.1	0.744
1/100	250.1	0.759
1/67	248.0	0.753

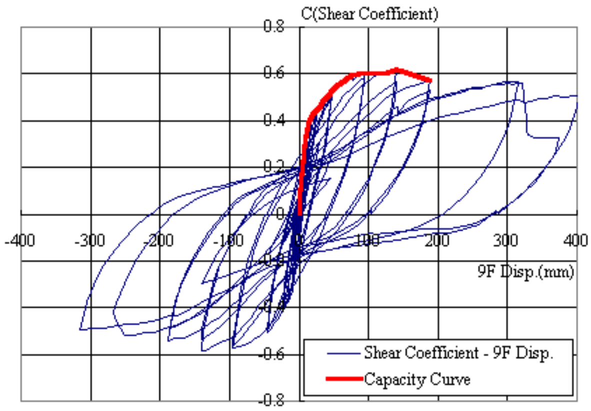


Figure 5: Capacity Curve (12-story test).

Damping Factor

Damping factor of HWS building (i.e., overall system) is evaluated from hysteresis damping of coupling beams and shear walls considering those energy absorption mechanisms. It is calculated by summation of hysteresis damping of coupling beams and those of shear walls considering their strain energy, and it is defined with equation (5).

$${}_sh = \frac{{}_wh \cdot {}_wW + {}_bh \cdot {}_bW}{{}_wW + {}_bW} \qquad \text{----------(5)}$$

where, ${}_sh$: *Damping Factor of Overall System*
${}_wh$: *Damping Factor of Shear Walls*
${}_bh$: *Damping Factor of Coupling Beams*
${}_wW$: *Strain Energy of Shear Walls*
${}_bW$: *Strain Energy of Coupling Beams*

In table 2, equivalent damping factors of coupling beams (i.e., ${}_bheq$) on 12-story test, those of shear walls (i.e., ${}_wheq$), those of overall system (i.e., ${}_sheq$ from equation (5)), and those of SDOF system (i.e., ${}_eheq$) are shown (at R=1/400, 1/200, 1/100, 1/67). Equivalent damping factor is calculated by strain energy and hysteresis absorption energy based on equation (6) and figure 6. Equivalent damping factors of coupling beams are calculated by shear force v.s. displacement at each floor in 2nd loop. Equivalent damping factors of shear walls are calculated by moment v.s. story rotational angle and shear force v.s. story shear displacement at each story in 2nd loop. Equivalent damping factors of overall system are calculated by ${}_bheq$ and ${}_wheq$ from equation (5). Equivalent damping factors as SDOF system from test results are calculated by base shear force v.s. displacement at 9th floor in 2nd loop. From table 2 ${}_sheq$ is nearly corresponding with ${}_eheq$, therefore it can be considered that damping factor of HWS building is evaluated by equation (5).

It is considered that *heq* calculated by test result can't be applied to this method directly, because real earthquake response are unstable response while test loading is stable. According to comparison between substitute damping obtained by real earthquake response (proposed by Shibata et al. i.e., *hs*) and *heq* calculated by hysteresis characteristic (i.e., *heqH*), *heqH* takes average value of *hs*. It is pointed out the lower limit value of *hs* [Shibata, A., 1976] should be taken for this method. Therefore, reduction factor for *heqH* is studied by the followings. Damping factor calculated by response spectrum and performance point by dynamic analysis of equivalent SDOF system of 12-story test specimen (i.e., *heqR*) is compared with *heqH*. The conditions of dynamic analysis are listed in table 4. The skeleton curve of equivalent SDOF system is modeled to trilinear curve from 12-story test result. The hysteresis characteristic is Takeda model. The unloading stiffness of Takeda model is decided so that damping factor of 12-story test result is corresponded with that of Takeda model calculated by hysteresis loop.

Table 2: Equivalent Damping Factor (12-story test).

		1/400			1/200			1/100			1/67		
		heq	W	ΔW	heq	W	ΔW	heq	W	ΔW	heq	W	ΔW
		%	kN·m	kN·m	%	kN·m	kN·m	%	kN·m	kN·m	%	kN·m	kN·m
Coupling Beam	${}_bh$	**17.44**	4.57	10.01	**26.27**	10.96	36.20	**29.60**	24.04	89.43	**26.57**	29.59	98.83
Shear Wall	${}_wh$	**5.66**	6.05	4.31	**6.69**	16.68	14.03	**13.60**	37.84	64.67	**16.03**	59.81	120.46
Overall System	${}_sh$	**10.73**	10.62	14.32	**14.46**	27.65	50.22	**19.82**	61.88	154.10	**19.52**	89.40	219.29
SDOF System	${}_eh$	**9.68**	11.23	13.66	**13.25**	28.06	46.73	**18.51**	62.58	145.58	**18.60**	90.91	212.48

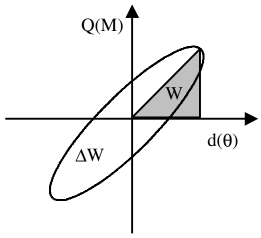


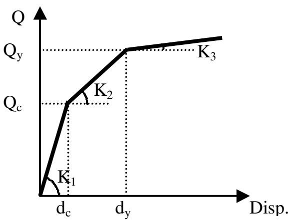
Figure 6: Equivalent Damping Factor.

$$heq = \frac{1}{4\pi} \cdot \frac{\Delta W}{W} \quad \text{------(6)}$$

where, ΔW : *Hysteresis Absorption Energy*
W : *Strain Energy*

Table 3: Conditions of Dynamic Analysis.

Hysteresis Characteristic	K1(kN/mm)	Qc(kN)	Qy(kN)	K2/K1	K3/K1
	80.3	756.0	1035.0	0.524	0.082
	Takeda Model (Unloading Stiffness Coefficient γ=0.4)				
Mass	239.2(N·sec2/mm)				
Earthquake Wave			Maximum Velocity (kine)		
	NewRC Wave		25.0	50.0	75.0
	1940 El Centro- NS				
	1952 Taft-EW				
	1968 Hachinohe-NS				
Damping	Current Stiffness Proportional Damping (h1=0.03)				



Response spectrum, performance point of dynamic analysis of equivalent SDOF system of 12-story test specimen against *50kine NewRC Wave* [National Land Development Engineering Research Center, 1993], and relationship of damping factor v.s. displacement are shown in figure 7. From figure 7, performance point is located on the response spectrum with damping factor of 15 % , and then *heqR-NewRC* is estimated about *15%*. At the time of performance point, *heqH-NewRC* is obtained about *17%* from relationship of damping factor v.s. displacement in figure 7. Relationship of *heqR* and *heqH* about the response against other earthquake waves are shown in figure 8. From figure 8, it is decided that reduction coefficient of *heqH* for this method is *0.8*. Relationship of *heqH* v.s. ductility factor of coupling beams at each floor on 12-story test are shown in figure 9, and those of shear walls are shown in figure 10. It is defined that ductility factor is a ratio of tension rebar yielding. Damping factor of each element can be nearly defined by equation (7) as a lower limit value of *0.8heqH*.

$$h = \frac{1}{\pi}\left(1 - \frac{1}{\sqrt{\mu}}\right) + 0.02 \qquad \text{----------(7)}$$

where, μ *Ductility Factor*

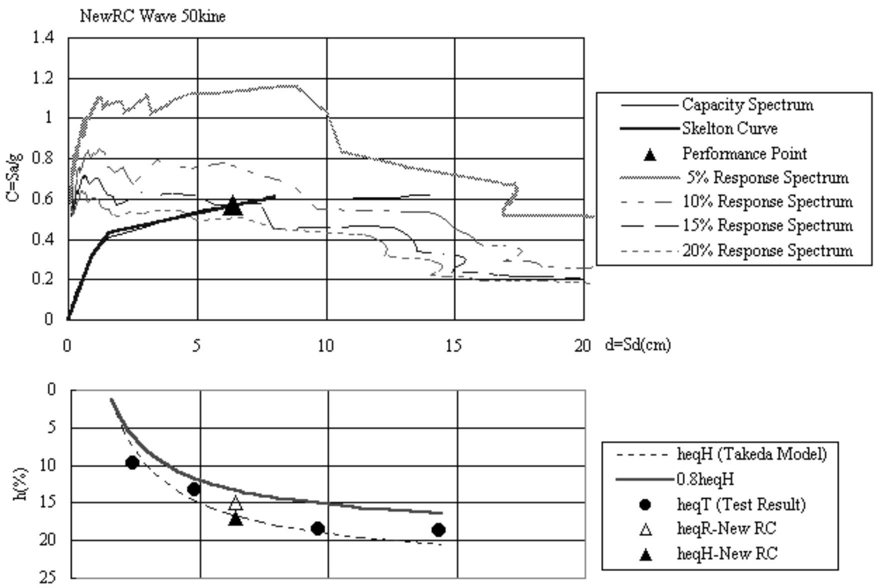


Figure 7: Response Spectrum, Maximum Response of Dynamic Analysis of Equivalent SDOF System and Damping Factor v.s. Displacement.

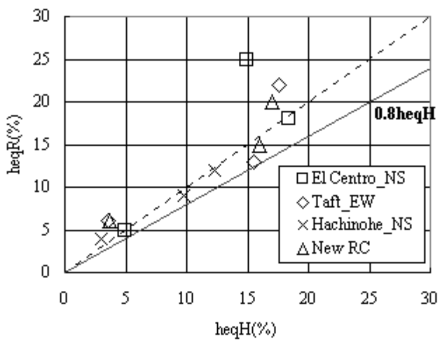


Figure 8: Comparison of *heqH* and *heqR* .

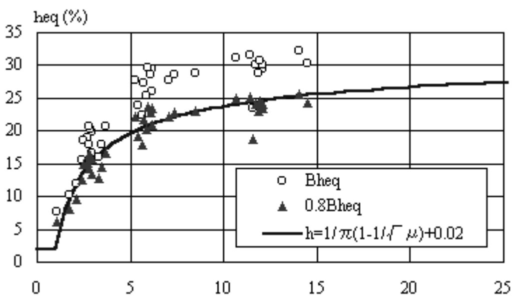


Figure 9: *heqH* v.s. Ductility Factor. (Coupling Beams on 12-story Test)

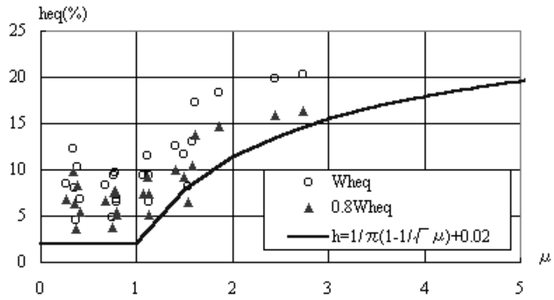


Figure 10: *heqH* v.s. Ductility Factor. (Shear Walls on 12-story Test)

Therefore, damping factor of HWS building for this method is calculated by equation (5) that is summation of equation (7) about each element considering their strain energy. Damping factor for this method calculated by equations (5) and (7) on 12-story test, $_{s}heq$, and $_{e}heq$ are shown in figure 11. Damping factor by equations (5) and (7) on 12-story test is smaller than $0.8_{s}heq$ and $0.8_{e}heq$ from figure 11. Damping factor for this method is evaluated smaller than reduction damping factor by hysteresis characteristic.

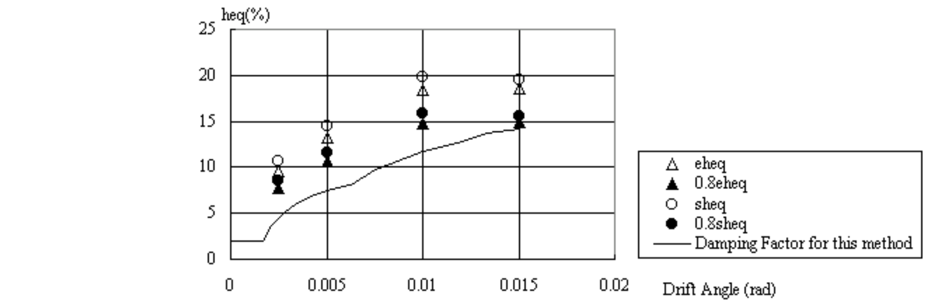


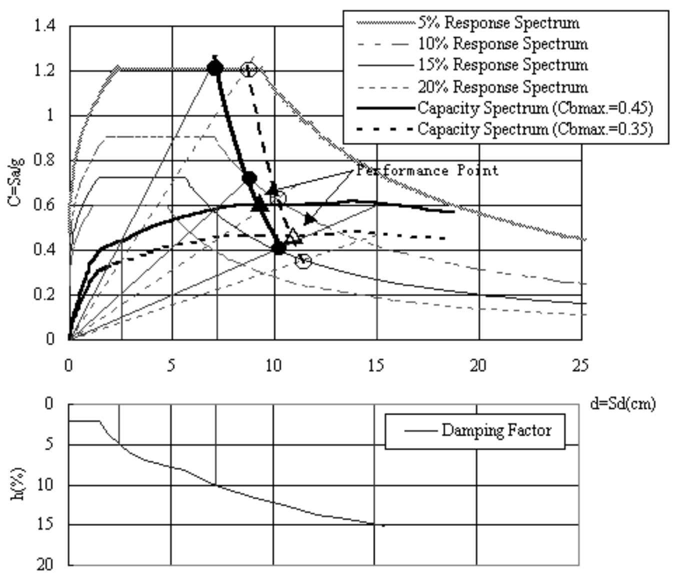
Figure 11: Damping Factor of 12-story Test Specimen for this Method v.s. Drift Angle.

Estimation of Performance Point

The performance point for HWS building can be estimated by capacity curve and demand curve considering hysteresis damping effect. It is defined as the crossing point of capacity curve and demand curve. For example, the performance point for equivalent SDOF system of 12-story test specimen is estimated against demand curve with maximum velocity level of about *50kine*. Demand curve is calculated from acceleration response spectrum proposed by AIJ Recommendation for Loads on Building [Architectural Institute of Japan, 1996]. Parameters for calculating demand curve are shown in table 4. Capacity curve is represented by relationship of shear coefficient v.s. displacement on equivalent SDOF system in figure 5. Damping factor is calculated by equations (5) and (7) in figure 11.

Table 4: Parameters for Demand Curve.

Site	Tokyo
Return Period	350 years
Soil Type	Type 2 (Soft Diluvial or Firm Alluvial Soil)
Damping Factor	5%, 10%, 15%, 20%
Maximum Velocity	52.45 kine



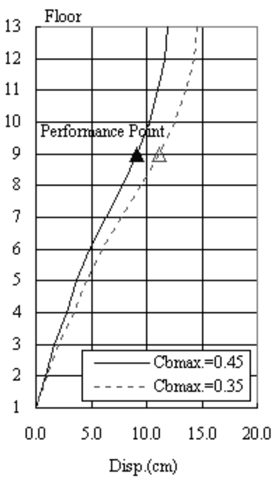


Figure 12: Performance Point for Equivalent SDOF System of 12-story Test Specimen against Demand Curve.

Figure 13: Each Story Displacements of Performance Point.

The performance point for equivalent SDOF system of 12-story test specimen estimated by this method against its demand curve is shown in figure 12. The maximum displacement is about *9cm*, and the maximum drift angle is about *1/100* respectively. The overall seismic performance against its demand earthquake motion is so stable that maximum response is smaller than maximum value of capacity curve. Each story displacements of performance point are estimated by maximum displacement of equivalent SDOF system and its deformation mode. Each story displacements of performance point on 12-story test specimen are shown in figure 13.

The maximum base shear coefficient of 12-story test specimen was recorded about *0.45*. Considering large deformation capacity and efficient energy absorption of HWS building, it is possible that the HWS system can be designed with maximum base shear coefficient of *0.35*. The performance point for equivalent SDOF system of 12-story test specimen whose maximum base shear coefficient is modified to about *0.35* is estimated by this method, and the results is shown in figure 12. The maximum displacement is about *11cm*, and the maximum drift angle is about *1/90* respectively. Its overall seismic performance is still stable that maximum response is smaller than maximum value of capacity curve as well. Therefore, the reinforced concrete building with shear walls like HWS building that has high deformation performance and efficient energy absorption performance can be designed rationally by this seismic performance evaluation method.

CONCLUSIONS

The seismic performance evaluation method for HWS building is proposed. The overall seismic performance for HWS building is estimated by capacity curve and demand curve considering hysteresis damping effect.

1. Capacity curve is represented by relationship of shear coefficient v.s. displacement on equivalent SDOF system. Representative shear coefficient is base shear force divided by effective 1st mode mass and gravity acceleration, and representative displacement is displacement on height where participation function for 1st mode equal to 1.0 $({}_1\beta \cdot {}_1u_i) = 1.0$
2. Demand curve is represented by relationship of acceleration (Sa) and displacement (Sd) response spectrum considering hysteresis damping effect of the building in each drift level.
3. Damping factor of HWS building is evaluated from hysteresis damping of coupling beams and shear walls considering those energy absorption mechanisms, and it is calculated by summation of hysteresis damping of coupling beams and those of shear walls considering their strain energy.

Besides, it can be confirmed adequacy of this performance evaluation method by evaluation to 12-story coupled shear wall test specimen as application example.

4. The overall seismic performance of HWS building can be evaluated correctly by this method, because the predominant mode, the effective 1st mode mass, and equivalent height of HWS building is doesn't change from elastic region to plastic region and overall structural characteristic is suitable to be represented by equivalent SDOF system.
5. Each story displacements of performance point are estimated by maximum displacement of equivalent SDOF system and its deformation mode.
6. The reinforced concrete building with shear walls like HWS building that has high deformation capacity and efficient energy absorption can be designed rationally by this seismic performance evaluation method.

ACKNOWLEDGEMENT

This work has been financially supported by US-Japan Cooperative Structural Research Project on Composite and Hybrid Structure. The authors would like to acknowledge Prof. H. Aoyama, chairman of Technical Coordinating Committee, Prof. A. Wada, chairman of Hybrid Wall System Technical Sub-Committee, Prof. T. Kabeyasawa, sub-chairman of that, and all members of the project for their useful advises and suggestions.

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