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Base shear amplification effect of slender RC shear wall

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ABSTRACT

In performance based seismic design of slender RC walls, nonlinear time history analysis generates the shear force requirement greater than that of elastic modal analysis. In this study, to investigate the factors contributed to the shear amplification effect, a numerical parameter study was performed considering four parameters: total number of stories, fundamental period, flexural over-strength ratio and soil condition. Nonlinear time history analysis was carried out by using 20 ground motions. The result showed that the major parameters influencing the shear amplification effect were the total number of stories and flexural over-strength ratio. On the basis of the result, an equation of base shear amplification factor was proposed as a function of the number of stories and flexural over-strength ratio. The proposed method predicted better the amplified shear force under nonlinear dynamic behavior, rather than existing methods.

1. INTRODUCTION

In the performance based design (PBD), in order to evaluate seismic response of a structure, nonlinear time history analysis (NTHA) should be carried out by using actual ground motions. However in the case of slender reinforced concrete (RC) wall structures, shear force distribution resulted from NTHA tends to be amplified more than two to three times of that from linear response spectrum analysis (RSA).

In the design codes of Europe and New Zealand, in order to consider this shear amplification effect of RC wall structure, shear amplification coefficient and distribution model are specified. On the other hand, in Korea, even majority of residential buildings are slender RC wall structure, nonlinear dynamic behavior of slender RC walls is not considered in the seismic design process. In this study, to investigate the factors contributed to the shear amplification effect, a numerical parameter study was performed. Based on the result, an equation for base shear amplification factor was suggested.

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2. ANALYSIS PLAN

2.1 Major analytical parameters

In the present study, influence of four analytical parameters that may affect the shear amplification effect of slender RC walls; total number of stories, first order modal period, flexural over-strength ratio and soil condition. Table 1 shows range of value of each parameters corresponding to actual design case of slender RC shear walls.

Table 1 Analytical parameters

Number of Stories N	Natural period T_1 (sec)	Soil condition SC*	Moment over-strength ratio γ_w
10F	0.5	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5, 3.0
		S_D	1.2, 1.3, 1.4, 1.5, 1.8
	0.7	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0
		S_D	1.2, 1.3, 1.4, 1.5
	1.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8
		S_D	1.2, 1.3, 1.4
15F	1.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5, 3.0
		S_D	1.2, 1.3, 1.4, 1.5, 1.8
	1.5	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0
		S_D	1.2, 1.3, 1.4, 1.5
	2.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8
		S_D	1.2, 1.3, 1.4
20F	1.5	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5, 3.0
		S_D	1.2, 1.3, 1.4, 1.5, 1.8, 2.0
	2.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5
		S_D	1.2, 1.3, 1.4, 1.5, 1.8
	3.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0
		S_D	1.2, 1.3, 1.4, 1.5
30F	2.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5, 3.0
		S_D	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5
	3.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5, 3.0
		S_D	1.2, 1.3, 1.4, 1.5, 1.8, 2.0
	4.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5
		S_D	1.2, 1.3, 1.4, 1.5, 1.8
40F	3.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5, 3.0
		S_D	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5, 3.0
	4.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5, 3.0
		S_D	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5
	5.0	S_B	1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5, 3.0
		S_D	1.2, 1.3, 1.4, 1.5, 1.8, 2.0

* S_B : Rock condition , S_D : Stiff soil condition

Shear amplification occur by higher mode effect after yielding of wall base. Total number of stories and first order modal period were considered as factors increasing influence of higher mode. Five cases of total number of stories were considered; 10 stories, 15 stories, 20 stories, 30 stories and 40 stories. First order modal period was calculated from each analytical model and it is within the maximum natural period limit specified in the design code.

Flexural over-strength ratio was considered as a factor increasing flexural strength of wall base. It is calculated by dividing the flexural capacity of wall base (Mn) by the flexural demand (Mu). In accordance with Boivin et al, since the influence of axial force ratio on the nonlinear dynamic response of shear force, it is able to determine the flexural capacity by adjusting the axial force ratio. In order to simplify the process of establishing analytical models, for the analytical model with the same wall reinforcement, the flexural over-strength ratio was determined by adjusting the axial force ratio. Instead, axial force ratio was limited to less than 20% to minimize the secondary moment by the nonlinear geometric effect. By these conditions, flexural over-strength ratio was determined among 1.2, 1.3, 1.4, 1.5, 1.8, 2.0, 2.5 and 3.0 within the axial force ratio range of 0 to 20%

Two soil conditions were considered; rock bed and solid soil where the majority of residential RC wall buildings are constructed. Input ground motions corresponding to soil conditions are applied.

2.2 Analytical model

By using structural analysis program, Perform 3Dm, analytical models were established and the nonlinear time history analysis was carried out. Fig.1 (a) shows the configuration of analytical model. Simplified 2-dimensional cantilever wall model was used. For this, torsional, out of plane directional and out of plane bending degree of freedom were constrained. At the base of wall model, fixed boundary condition was applied.

Fig.1 (b) shows the cross-sectional detail of wall model. By using fiber model method, five fibers for concrete and ten fibers for reinforcing steel was modeled. By applying capacity design concept, the wall sections were designed to be yield only at the wall base. To prevent the upper walls from yielding first, the upper walls were designed to have the flexural over-strength ratio 1.1 times greater than that of wall base.

2.3 Material model

In the perform 3D, a wall element consists of an inelastic section element and a shear material element. The inelastic section element defines stress-strain relationships of uniaxial behavior of the concrete and the reinforcing steel in the wall section. The shear material element defines a shear stiffness of the wall. Fig.1 (c) shows a multi-linear stress-strain relationship of concrete fitted with Kent-park concrete model. The ultimate strength f_{ck} was 21 MPa and elastic modulus of concrete was 24,800 MPa. A tensile strength of concrete and a confinement effect of concrete were not considered.

Fig.1 (d) shows a strain-stress relationships of reinforcing steel. An elasto-plastic strain-stress relationship was defined for tensile behavior of reinforcing steel. The yield strength Fy was 400 MPa and the elastic modulus was 200,000 MPa. A strain hardening effect and fracture strength of reinforcing steel were not considered. To considered the buckling of reinforcing steel after concrete crushing, compressive strength was assumed to reduce after the compressive strain reaches to 0.003

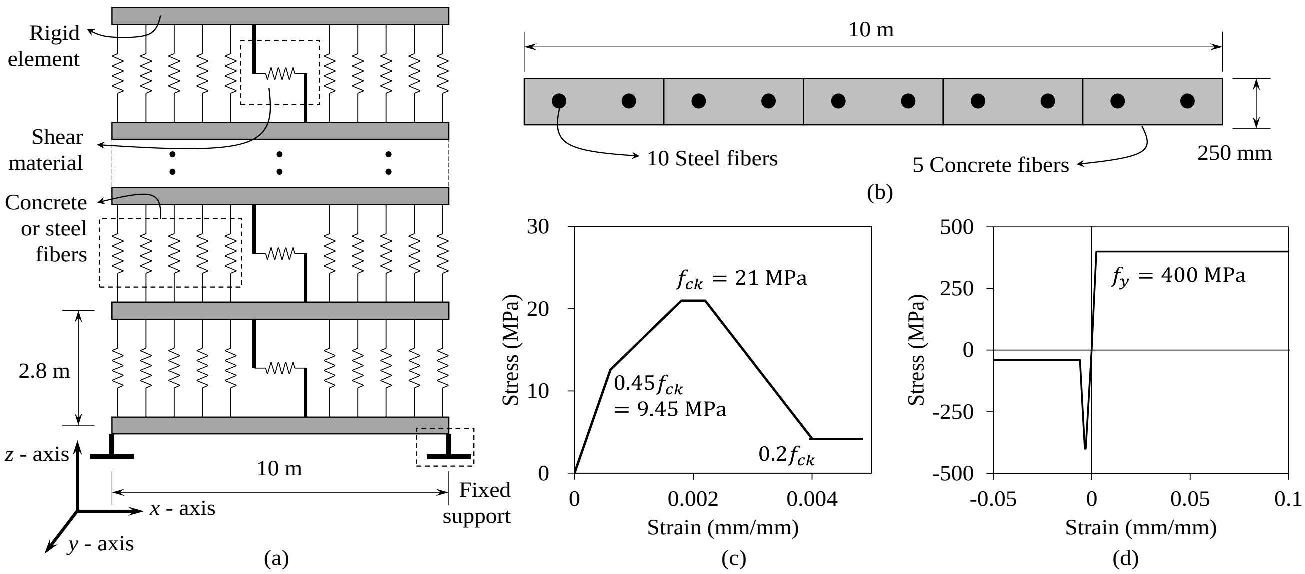

Fig. 1 Configuration of analysis model: (a) Fiber method model; (b) Cross-sectional property of wall; (c) Material model for concrete; (d) Material model for reinforcing bar.

In order to lead the flexural failure of the wall, the shear material element of wall was assumed to be an elastic material. The shear stiffness of wall was 10640 MPa with poisson's ratio of 0.167

2.4 Input ground motions

The input ground motions for nonlinear time history analysis were selected in consideration of the shear wave velocity, the distance from the epicenter and the magnitude of the event. According to Korean Building Code (KBC 016), shear wave velocity was 760~1500 m/s for soil condition of SB and 180~360 m/s for soil condition of SC. The distance from the epicenter was 0 ~ 100 km and the magnitude of event was 6.0~7.5 M.

For each soil condition, ten pairs of ground motions matching with design spectrum were selected. Response spectra corresponding to the individual components of each pair of ground motions were created. Fig.2 shows the response spectra of 20 input ground motions and average spectrum of them. Each ground motion was scaled such that average spectrum was not less the design spectrum for periods ranging from 0.25 to 7.5 sec.

3. ANALYSIS RESULTS

The nonlinear time history analysis was performed on 184 analytical models with 20 selected ground motions. In this study, the shear force amplification effect by nonlinear dynamic behavior was assumed to be the sum of shear force component by elastic modal analysis and shear force component by influence of higher mode after yielding. Therefore, the amplified bottom surface shear force V_a can be expressed by Eq. (1).

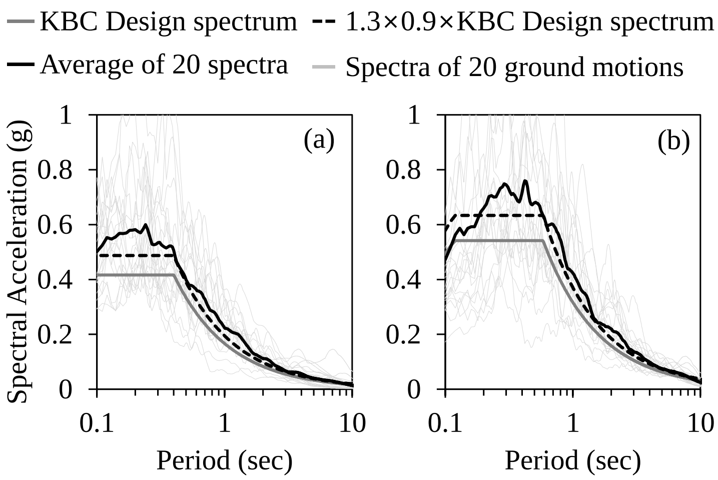

Fig. 2 Average of 20 scaled spectra: (a) S_B soil condition; (b) S_D soil condition

$$V_a = V_y + V_{yp}\omega_{vh} \quad (1)$$

Where V_a was an amplified shear force by shear amplification effect, V_y was a shear force component at flexural yielding of the wall and V_{yp} was a shear force component calculated from pinned base wall model. In the pinned base wall model, lateral stiffness of wall in the first floor was reduced to 10% of original lateral stiffness to simulate the generation of plastic hinge at the wall base. For simplified design without pinned base model, V_{yp} can be replaced to V_y^* which was calculated by combining modal response except for first modal response in the original wall model. ω_{vh} is a higher mode effect coefficient.

By dividing the amplified shear force to two shear force components, relationship between the analytical parameters and the higher mode effect was analyzed. From the Eq. (1), the base shear amplification factor (ω_v) and the higher mode effect (ω_{vh}) were defined as follows:

$$\omega_v = V_a/V_y \quad (2)$$

$$\omega_{vh} = (V_a - V_y)/V_{yp} \quad (3)$$

3.1 Effect of total number of stories (N)

Fig. 3 shows the relationship between total number of stories (N) and base shear amplification factor (ω_v) and higher mode effect (ω_{vh}). The difference of response due to first modal period was not large in the same total number of stories (N). In Fig.4 (a), the base shear amplification factor (ω_v) decreased as the total number of stories (N) increased independently with flexural over-strength ratio. However, when the total number of stories (N) was 10, where the flexural yielding of wall didn't occur sufficiently for most of input ground motions, base shear amplification factor (ω_v) was relatively small. In Fig.4 (b), the higher mode effect (ω_{vh}) showed the largest value of 2.72 when

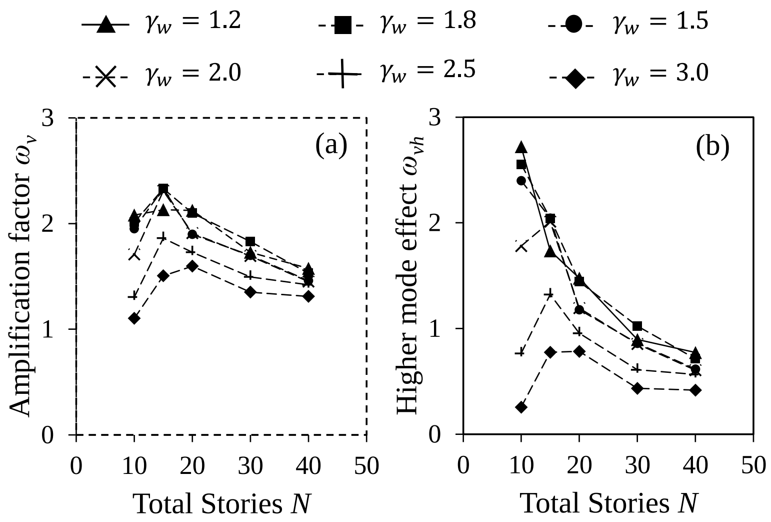

Fig. 3 Influence of the total number of stories and 1st mode period on seismic response: (a) Shear amplification ($\boldsymbol{\omega_v}$) according to total stories ($\boldsymbol{N}$); (b) Higher mode effect ($\boldsymbol{\omega_{vh}}$) according to total stories ($\boldsymbol{N}$)

the total number of stories (N) was 10 and the flexural over-strength ratio (γ_w) was 1.2, and decreased with increasing number of stories. However, However, in some analytical models (N = 10; γ_w = 2.0, 2.5, 3.0) where wall flexural yielding did not occur sufficiently, the higher mode effect (ω_{vh}) was small. This indicates that the shear amplification effect by nonlinear dynamic behavior is not large when the flexural yielding of the wall base does not sufficiently occur due to the high flexural over-strength ratio.

3.2 Effect of flexural over-strength ratio

Fig.4 shows the relationship between flexural over-strength ratio (γ_w) and the base shear amplification factor (ω_v), the higher mode effect (ω_{vh}) and shear force distribution. In the case of the same spectral acceleration, the lower the flexural over-strength ratio, the easier the flexural yielding of the wall base and the greater amplified shear force. For this reason, the base shear amplification factor (ω_v) was tend to be linearly decreased as the flexural over-strength ratio (γ_w) increased. The higher mode effect (ω_{vh}) was relatively constant with flexural over-strength ratio (γ_w) (γ_w = 1.2, 1.3, 1.4, 1.5), and decreased with increasing flexural over-strength ratio. Also, the influence of the first modal period on higher mode effect was not large when the flexural over-strength ratio was constant.

When the total number of stories was small (N=10, 20) relative distribution of story shear force on the base shear force was not significantly affected by the flexural over strength ratio. On the other hand, when the total number of stories was high (N=40), the shear force amplification occurred more in the lower part than in the upper part.

4. PROPOSED MODEL FOR SHEAR FORCE AMPLIFICATION

Base on analysis results, the total number of stories (N) and the flexural over-strength ratio (γ_w) were major parameters affecting the higher mode effect. From this,

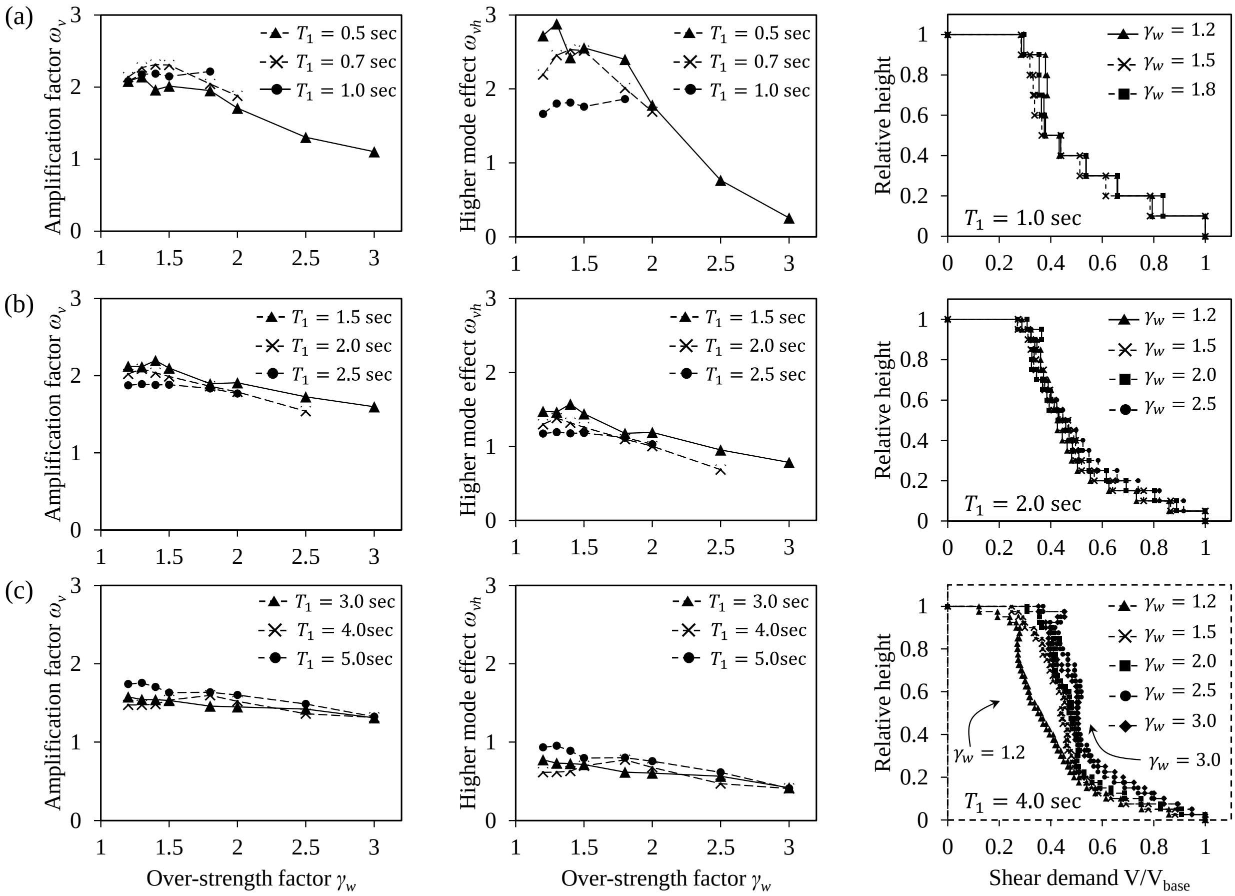

Fig. 4 Influence of moment over-strength of the wall base on amplification factor, higher mode effect and vertical shear distribution: (a) *N*=10; (b) *N*=20; (c) *N*=40.

design equation for base shear amplification factor was suggested. The proposed design equation and was compared with the prediction models of EC8 and Rutenberg and Nsieri.

Fig. 5 shows the relationship between average higher mode effect and the total number of stories and the flexural over-strength ratio. The higher mode effect tended to decrease inversely with the total number of stories. Also, the higher mode effect was constant when the flexural over-strength ratio was less than 1.5 and linearly decreased when the flexural over-strength ratio was more than 1.5. In this study, influence of total number of stories and flexural over-strength ratio were independently considered for the calculation of the higher mode effect.

$$\omega_{vh} = (a\gamma_w + b)N^c \ \ (\gamma_w \geq 1.5) \tag{4}$$

Where a, b and c were calibration factors determined by multiple regression analysis. The values were a=-3.2, b=16, c=0.6. For the conservative design, the value of the calibration factor a was determined so that the ratio of the data whose predicted higher mode effect was less than the actual higher mode effect was less than 5%. When the flexural over-strength ratio was smaller than 1.5, γ_w=1.5 was applied.

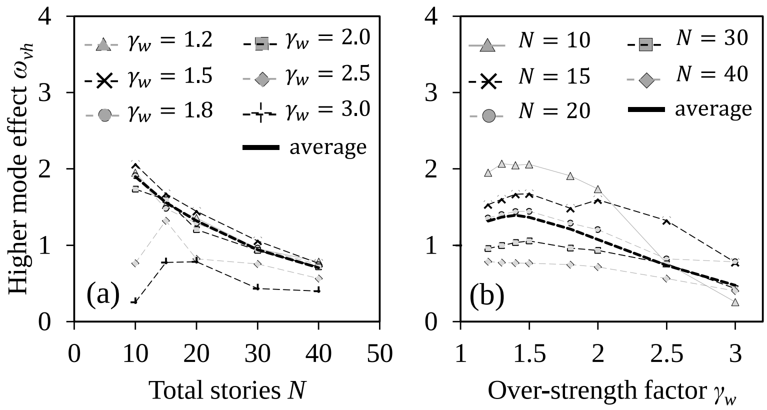

Fig. 5 Influence of main parameters on higher mode effect : (a) Relationship between *N* and $\boldsymbol{\omega_{vh}}$; (b) Relationship between $\boldsymbol{\gamma_w}$ and $\boldsymbol{\omega_{vh}}$.

The base shear amplification factor (ω_v) was derived from Eq. (2), Eq. (3) and Eq. (4) as follows.

$$\omega_v = 1 + (-3.2\gamma_w + 16)N^{0.6}\frac{V_{yp}}{V_y} \tag{5}$$

In the case of design the wall without considering pinned base model, V_{yp} can be replaced to V_y^* which was calculated by combining modal response except for first modal response in the original wall model.

$$\omega_v = 1 + (-3.2\gamma_w + 16)N^{0.6}\frac{V_y^*}{V_y} \tag{6}$$

Fig.7 shows the strength ratios of the analysis results predicted by the proposed equations (Eq. (5) and Eq. (6)). The proposed equations reasonably agreed with the analysis results regardless of natural period and flexural over strength ratio.

5. CONCLUSION

In this study, the design of base shear force considering the nonlinear shear force amplification effect was proposed to accurately estimate the wall required shear force due to seismic load at preliminary design. For this purpose, a total of 184 analytical models were established by combining four variables: total number of stories, first order modal period, flexural over-strength ratio and soil condition. The nonlinear time history analysis was performed using 20 ground motions corresponding to each soil condition. The details of the study are as follows.

1) The wall shear force amplified by the nonlinear dynamic behavior is defined as the sum of the shear force component by the flexural yielding of the wall (V_y) and shear force component calculated from pinned base wall model (V_{yp}). By this method, the

effect of the higher order modes due to the nonlinear behavior after yielding of the wall base was considered independently.

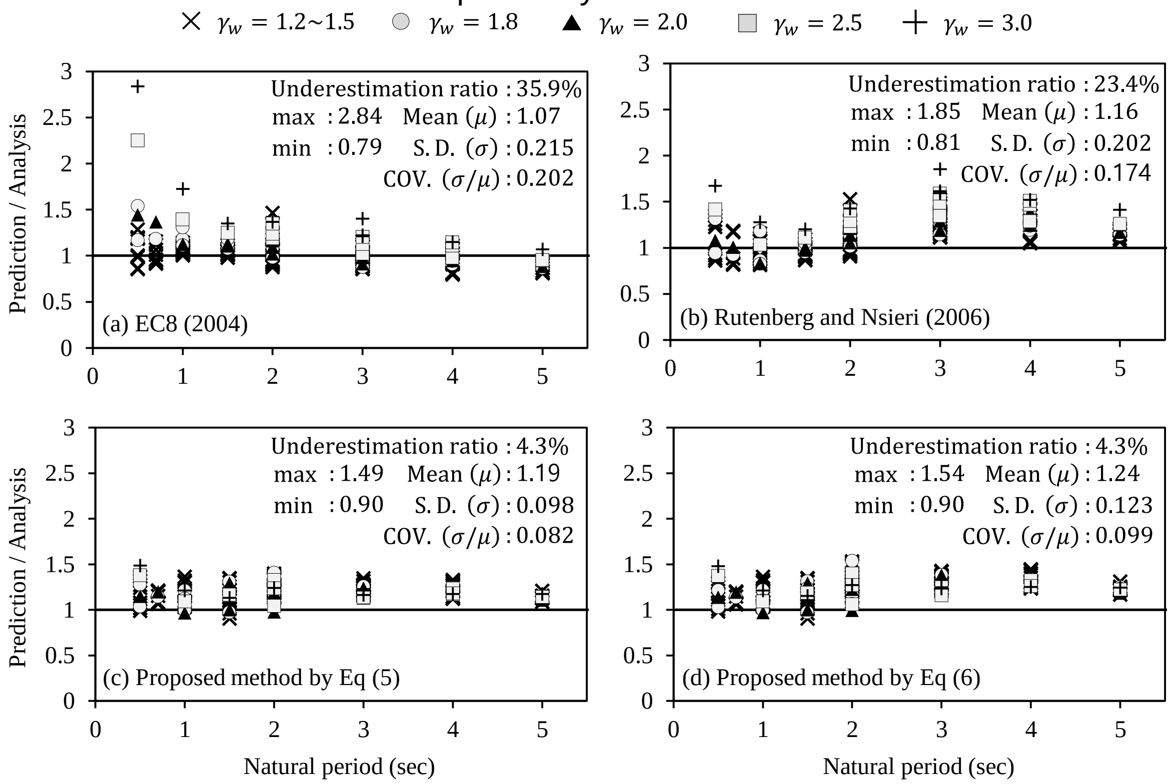

Fig. 6 Comparison of amplification factor between analysis and predictions: (a) EC8 (2004); (b) Rutenberg and Nsieri (2006); (c) Proposed method by Eq (5); (d) Proposed method by Eq (6).

2) The shear force amplification effect was manly affected by two major parameters: the total number of stories and the flexural over strength ratio. The higher mode effect was decreased as the total number of stories increased. Also, it was constant as the flexural over strength ratio was smaller than 1.5, and decreased with flexural over strength ratio greater than 1.5. When the flexural over-strength ratio was not large enough to occur flexural yielding of wall, the higher mode effect was drastically decreased.
3) Based on the results of nonlinear time history analysis, the higher mode effect and the base shear force amplification factor were proposed. In the proposed method, the influence of the total number of stories and the flexural over-strength ratio were considered independently. The proposed method predicts the base shear force amplification effect to the safe side within a small error range than the existing method.

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