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Vertical distribution of equivalent static loads for base isolated building structures

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Abstract

It has been pointed out that the static lateral response procedure for a base isolated structure presented in UBC-97 somewhat overestimates the seismic story force. In this study the UBC-91 and UBC-97 static lateral load procedures for isolated structures are investigated, and a new formula is proposed for the vertical distribution of seismic load. The formula is derived by combining the fundamental mode shape of the isolated structure idealized as two degrees of freedom system and the fundamental mode shape of a fixed-based structure. The seismic story forces resulting from the proposed method are compared with those obtained from dynamic time history analysis and the code procedures. The results show that the proposed method provides conservative results compared with those from dynamic analysis and UBC-91 approach, and produces a more economic solution compared with the UBC-97 static lateral response procedure. © 2001 Published by Elsevier Science Ltd.

Keywords: Base isolated structures; Static lateral response procedure; Vertical distribution of seismic force; UBC-91; UBC-97

1. Introduction

Seismic isolation mitigates earthquake-induced responses based on the concept of reducing the seismic demand by shifting the primary period of the structure rather than increasing the earthquake resistance capacity of the structure. The application of this technology may keep the building to remain essentially elastic and thus ensure safety during large earthquakes. The effectiveness has been verified by extensive researches and successful applications to many structures [1].

In the United States, the Structural Engineers Association of Northern California (SEAONC) produced a document entitled *Tentative Seismic Isolation Design Requirements* [2] in 1986. This document was based on the basic theory of seismic isolation, and the earthquake loads were uniformly distributed along the height. In 1988 the Seismology Committee of the Structural Engineers Association of California (SEAOC) formed a subcommittee to make an isolation design document entitled *General Requirements for the Design and Construction of Seismic Isolated Structures* [3]. This was later adopted as an appendix to the seismic provisions in the 1991 Uniform Building Code (UBC-91) [4]. In UBC-94 [5], the vertical distribution of base shear was changed from an uniform one to a triangular one, which is generally used for fixed-base structures and produces very conservative load distribution. Similar concept has been continued in UBC-97 [6]. In the current IBC (International Building Code) 2000 [7], the same load distribution method with UBC-97 is followed. Some researchers, however, are concerned about the trend that the codes governing the design of seismic isolated structures tend to be more conservative than those for conventional structures, since the conservatism may prevent the benefit of seismic isolation from being realized [8].

This paper presents a thorough investigation of the vertical load distribution of the static lateral response procedure specified in the UBC-91 and 97 (and therefore the IBC 2000), and proposes a more rational formula for the distribution of seismic force based on the dynamics of a two-mass system. The proposed method may be applied, at least in preliminary analysis and design phase, to the linear isolation system that includes natural rubber isolators with moderate linear viscous damping.

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2. Vertical load distribution specified in UBC-91 and 97

UBC-91 allowed the use of static analysis for a structure located farther than 15 km (9.4 miles) from an active fault, on soil profile type S1 and S2, with seismic zone factors 3 and 4 [4]. It emphasized a simple, statically equivalent method of design that took advantage of the fact that for a seismic isolated structure the displacement is concentrated at the base and the upper structure moves like a rigid body. This phenomenon results in a simple design procedure of an isolated structure based on a single vibration mode. The design forces for the super-structure are computed from the forces in the isolators at the design displacement D (in inches) computed from the following formula [4]:

$$D=\frac{10ZNS_{\mathrm{I}}T_{\mathrm{I}}}{B} \tag{1}$$

where B is determined from damping in the isolators, S_I is the site soil profile coefficient, Z is the seismic zone factor, and N is the near field factor determined from the distance from an active fault and the expected magnitude of the earthquake. The natural period of the isolated structure T_{I} (in seconds) is computed from the stiffness of the isolators and the weight of the super-structure:

$$T_{\mathrm{I}}=2\pi\sqrt{\frac{W}{K_{\min}g}} \tag{2}$$

where W is the total seismic dead load, $K_{\min}$ is the minimum effective stiffness of the isolator, and g is the gravity constant. The term *effective* is used because the stiffness is determined from cyclic tests of the isolators. The design lateral shear forces for the structure below and above the isolators, V_{b} and V_{s}, respectively, are computed from the following formulas, respectively:

$$V_{\mathrm{b}}=\frac{K_{\max}D}{1.5} \tag{3}$$

$$V_{\mathrm{s}}=\frac{K_{\max}D}{R_{wI}} \tag{4}$$

where $K_{\max}$ and D are the maximum effective stiffness of the isolation system and the design displacement, respectively. The readers are referred to the reference [4] for further information about the definition of the variables. The response modification factor R_{wI} is obtained based on the type of lateral-force-resisting system of the super-structure. The vertical distribution of the inertial forces on the structural system was based on the assumption that the super-structure acts like a rigid body and that the accelerations are the same at all floors. Based on this concept, the lateral force is distributed over the height proportional to the mass of the stories:

$$F_{\mathrm{x}}=\frac{w_{\mathrm{x}}}{\Sigma w_{\mathrm{i}}}\cdot V_{\mathrm{s}} \tag{5}$$

where w_{x} and w_{i} are the weight at level x and i, respectively. This, however, neglects the flexibility of the super-structure and the participation of the higher modes, and therefore may not guarantee enough safety in some cases [9,10].

In subsequent editions of the UBC the vertical distribution of force was changed due to the concern that the approach of UBC-91 might not be conservative enough. The UBC-97 seismic regulations for a seismic isolated structure are similar to those for general structures without seismic isolation. The static analysis procedure is permitted for structures located farther than 10 km (6.2 miles) from an active fault, with site soil profile type S_{A}, S_{B}, S_{C}, and S_{D}. The super-structure should be lower than 19.8 m (65 ft) in height, or the number of stories be less than or equal to four. For the isolated structure satisfying the above conditions, the minimum lateral earthquake displacements are computed in accordance with the formula [6]:

$$D_{\mathrm{D}}=\frac{\left(\frac{g}{4\pi^2}\right)C_{\mathrm{VD}}T_{\mathrm{D}}}{B_{\mathrm{D}}} \tag{6}$$

where B_{D} represents the effective damping of the isolation system at the design displacement. The seismic coefficient C_{VD} is determined from the seismic zone factor and the site soil profile type, and T_{D} is the effective period of the isolated structure at the design displacement, expressed similar to Eq. (2). Based on the design displacement, the minimum lateral forces below and above the isolation system are

$$V_{\mathrm{b}}=K_{\mathrm{Dmax}}D_{\mathrm{D}} \tag{7}$$

$$V_{\mathrm{S}}=\frac{K_{\mathrm{Dmax}}D_{\mathrm{D}}}{R_I} \tag{8}$$

where K_{Dmax} is the maximum effective stiffness of the isolation system at the design displacement, and R_I depends on the type of lateral-force-resisting system of super-structures. The coefficient R_I for a fixed-based structure has the value 2.2–8.5, however for a base-isolated structure a smaller value between 1.4 and 2.0 is used based on the assumption that the super-structure remains elastic. R_I differs from R_{wI} used in UBC-91 in that the former is determined based on the ultimate strength design concept while the latter is based on allowable stress design philosophy. The total lateral force above the isolation system V_{s} is distributed over the height of the structure in accordance with the formula

$$F_{\mathrm{x}}=\frac{w_{\mathrm{x}}h_{\mathrm{x}}}{\Sigma w_{\mathrm{i}}h_{\mathrm{i}}}\cdot V_{\mathrm{s}} \tag{9}$$

where w_{x} is the weight at level x, and h_{x} is the height above isolation level. This leads to a triangular distribution of the lateral loads, which accounts for the poss-

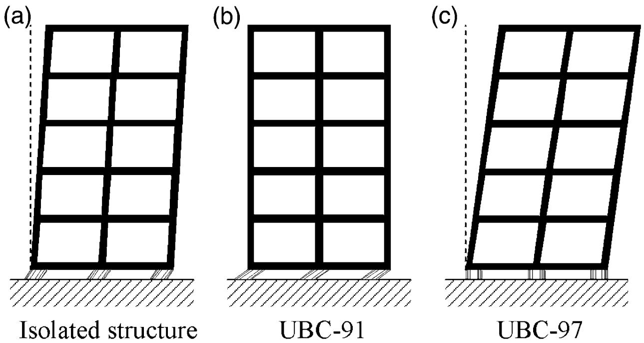

Fig. 1. Schematic behavior of a base-isolated structure subjected to a seismic load.

ible higher mode contributions generated by nonlinearities in the isolators. The current IBC-2000 adopted the same seismic load distribution procedure with the UBC-97 for the seismic isolated structures. Fig. 1 schematically describes the behavior of an isolated structure subjected to an earthquake load and the idealized ones on which the UBC-91 and the later versions are based. As will be shown later, these code approaches are somewhat inadequate; i.e. either not safe (UBC-91) or not economical (UBC-97 or IBC-2000).

3. Derivation of the proposed formula for vertical distribution of seismic loads

The proposed formula is based on the basic theory of structural dynamics of a two-mass model with linear seismic isolators as shown in Fig. 2. It is assumed that the effect of the off-diagonal components of damping matrix is negligible, which leads to simple procedure for structural response analysis. Usually the damping in a structure is assumed to be proportional to mass and/or stiffness of the structure. When base damping is introduced, the damping matrix of the overall system is no longer proportional, and the vibration modes become non-orthogonal leading to coupled modal responses. However, if the damping in the isolator is moderate, the required solution can be obtained from the uncoupled modal equations of motions after disregarding the off-diagonal terms in the damping matrix.

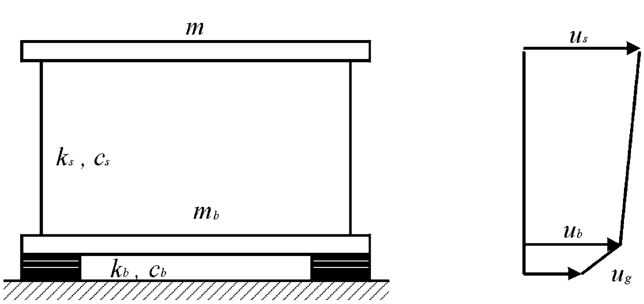

Fig. 2. Idealized two-mass system with seismic isolation.

The procedure for obtaining the natural frequencies and mode shape vectors of such a system is derived by Kelly [8]. He demonstrated that if a structure is modeled as systems with discrete masses and springs, it is possible to obtain approximate but accurate expressions for the mode shapes and frequencies of isolated structure in terms of fixed-based frequencies and mode shapes. In the given structural model shown in Fig. 2, m and m_b represent the mass of the super-structure and that of the base floor above the isolation system, respectively. The stiffness and damping of the structure are denoted by k_s and c_s, respectively, and those of the isolators are denoted by k_b and c_b, respectively. Absolute displacements of the two masses are represented by u_s and u_b, and the relative displacements are defined as

$$\mathbf{v}=\begin{pmatrix} u_s-u_g \\ u_s-u_b \end{pmatrix} \tag{10}$$

where u_g is the displacement of the ground. Using the above notations, the equation of motion of the two-mass structure becomes

$$\mathbf{M}\mathbf{v}+\mathbf{C}\mathbf{v}+\mathbf{K}\mathbf{v}=-\mathbf{M}\mathbf{r}\mathbf{u}_g \tag{11}$$

where

$$\mathbf{M}=\begin{bmatrix} M & m \\ m & m \end{bmatrix}, \mathbf{C}=\begin{bmatrix} c_b & 0 \\ 0 & c_s \end{bmatrix}, \mathbf{K}=\begin{bmatrix} k_b & 0 \\ 0 & k_s \end{bmatrix}, \mathbf{r}=\begin{pmatrix} 1 \\ 0 \end{pmatrix}, \text{ and } M$$
$$=m+m_b$$

The solution of the eigenvalue problem leads to the following expressions for the natural frequencies and the mode shape vectors [2]:

$$\omega_1^2=\omega_b^2(1-\gamma\varepsilon) \tag{12}$$

$$\omega_2^2=\frac{\omega_b^2}{1-\gamma}(1+\gamma\varepsilon) \tag{13}$$

$$\phi_1=\begin{pmatrix} 1 \\ 1+\varepsilon \end{pmatrix} \quad \phi_2=\begin{pmatrix} 1 \\ \frac{1}{\gamma}(1-\varepsilon)(1-\gamma) \end{pmatrix} \tag{14}$$

$$\varepsilon=\left(\frac{\omega_b}{\omega_s}\right)^2 \tag{15}$$

where the component of the mode shape vectors corresponding to the lateral displacement of the floor slab is normalized to be one for convenience, and the definition of each variable is given in Table 1. The above equations are obtained by neglecting the higher order terms of ε, the square of the frequency ratio, and the resultant mode shapes are plotted in Fig. 3. The variable ε represents

Table 1
Parameters used in the formulation for the dynamic characteristics

Natural frequency of isolation system	$\omega_b=\left(\frac{k_b}{M}\right)^{1/2}$
Natural frequency of super-structure	$\omega_s=\left(\frac{k_s}{m}\right)^{1/2}$
Mass ratio	$\gamma=\frac{m}{M}$
Square of frequency ratio	$\varepsilon=(\omega_b/\omega_s)^2$
Damping of isolation system	$2\omega_b\beta_b=\frac{c_b}{M}$
Damping of super-structure	$2\omega_s\beta_s=\frac{c_s}{m}$

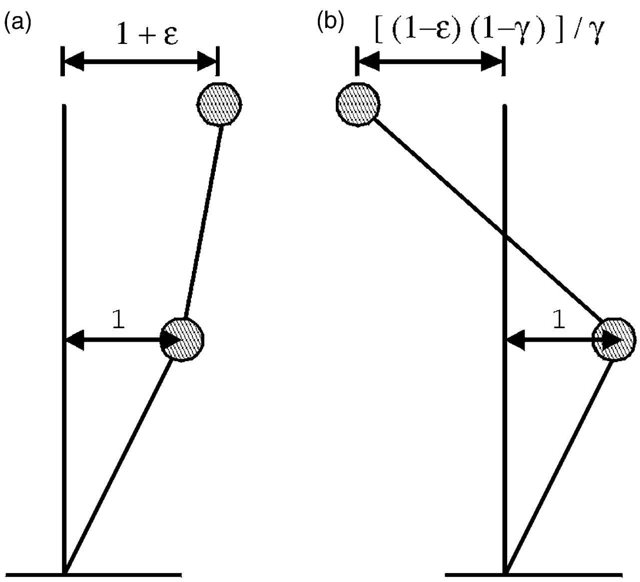

Fig. 3. Mode shapes for the two-mass system. (a) First mode; (b) second mode.

the vibration characteristics of the combined system of isolators and the super-structure. As the value of ε decreases, that is as the isolation system becomes stiffer, the combined system behaves more like a fixed structure.

The derivation of the proposed method starts from the idea that the fundamental mode shape of an isolated structure may be simulated by combining the fundamental mode shape of the fixed-based structure, assumed as linear, and that of the equivalent two-mass system shown in Fig. 3(a). Fig. 4 describes the combined mode shape of a general multi-story seismic isolated structure with the relative modal displacement at an effective height equal to the modal displacement at the top of the two-mass system. The effective height of a fixed-based structure corresponds to the height at which the lateral displacement is equal to that of the equivalent single degree of freedom system. The representative displacement of an equivalent single degree of freedom system, x_r, can be obtained as follows [11]:

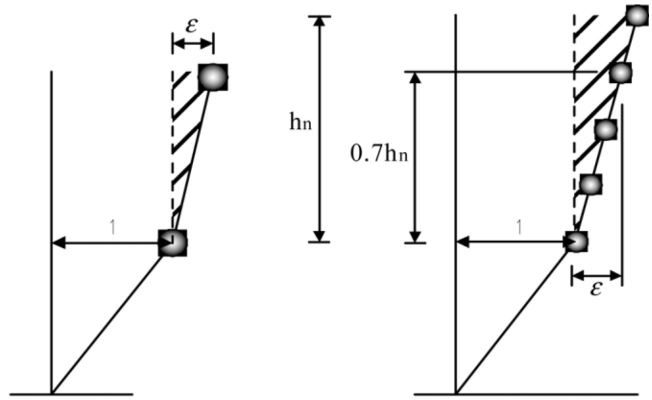

Fig. 4. Synthesis of fundamental mode shape of an isolated structure from that of the two-mass system. (a) Fundamental mode of two-mass system; (b) synthesized mode for isolated structure.

$$x_r=\frac{\sum_i m_i x_i^2}{\sum_i m_i x_i} \tag{16}$$

where m_i is the mass of the ith floor of a multi-story structure, and x_i is the maximum displacement of the ith floor. For regular structures the effective height is generally taken to be 0.7 h_n for a shear wall structure and 0.6 h_n for a framed structure [12], where h_n is the total height of the structure. Priestley and Kowalsky [12] presented a formula for more precise determination of effective height when mass or story heights vary significantly with height. Further comments on the effective height will be presented subsequently.

Based on this synthesized mode shape and with the effective height of αh_n the following formula is proposed for the seismic story force for a seismic isolated structure:

$$F_x=\frac{w_s(1+\varepsilon h_x/\alpha h_n)}{\Sigma w_i(1+\varepsilon h_i/\alpha h_n)}\cdot V_s \tag{17}$$

where α is generally taken to be 0.6 and 0.7 for framed and shear wall structures, respectively, and ε can be obtained from Eq. (15). Table 2 presents the relation between the ratio of the natural period of the super-structure and the isolated system described in Fig. 2, T_s/T_b, and the coefficient ε computed from Eq. (15) and from the mode shape vectors obtained from dynamic eigenvalue analysis. In the analysis the natural period of the isolation system, T_b, is fixed to 2 s. It can be noticed in the table that as the fundamental natural period of the super-structure decreases, i.e. as the structure becomes stiffer, the relative modal displacement, ε, also decreases. As mentioned above higher order terms are neglected in the derivation of Eq. (15), and the results are not exact. It can be observed, however, that the difference between the results of eigenvalue analysis and the simplified equation is negligible, especially when the

Table 2
Variation of ε for various period ratios

T_s/T_b	0.05	0.1	0.2	0.3	0.5	1.0	2.0
ε (approx.)	0.0025	0.010	0.040	0.090	0.250	1.000	4.000
ε (exact)	0.0025	0.009	0.040	0.091	0.255	1.049	4.319

period ratio is small (say less than 0.5), which corresponds to most of the seismic isolated structures. Therefore by using Eq. (15) the coefficient ε can be obtained accurately without carrying out eigenvalue analysis.

Suppose that the properties of the base-isolation system, such as mass of the super-structure, stiffness and damping of the isolators, etc., are predetermined, the seismic story force for general base-isolated multi-degree of freedom systems can be determined following the procedure summarized below:

1. Determine the design lateral shear force V_s from code formula
2. Determine the natural frequency of the isolation system, $\omega_b=\sqrt{\frac{k_b}{M}}$
3. Compute the natural frequency of the super-structure from code formula
4. Compute the coefficient ε from Eq. (15)
5. Determine effective height coefficient α
6. Obtain the seismic story force from the proposed formula, Eq. (17)

4. Verification of the proposed method with the results from dynamic analysis

To compare the seismic force distribution computed from the proposed formula with those obtained from the code procedures and from dynamic analysis, a five-story reinforced concrete framed structure and a shear wall structure described in Fig. 5(a,b) were analyzed first. Then for further verification of the proposed method a 15-story framed structure shown in Fig. 5(c) was also analyzed. The structures have 4×2 bays with each column or shear wall isolated on the base level by linear isolators. The floors were considered as rigid diaphragms with infinite in-plane stiffness. Only three degrees of freedom in each nodal point in a floor, i.e. two lateral degrees of freedom along the x and y axis and one rotational degree of freedom around the vertical axis, are transferred to the mass center, and the other degrees of freedom are condensed out to form a stick model with three degrees of freedom in each story. The representative height is taken to be 0.6 h_n for framed structures and 0.7 h_n for the shear wall structure, and 2% of the critical damping was assumed for the super-structures. The seismic loads are enforced along the short (y) direction. Table 3 lists the design parameters and their values used in the analysis. The periods are the effective ones at the design displacement obtained from the code formula.

Many practical isolation systems involve higher damping than that inherent in the structure. To see the effect of isolator damping on the vertical distribution of the seismic force, two viscous damping coefficients of isolators, 5% and 25% of the critical damping, were considered in the analysis. The former may correspond to the damping of the natural rubber isolators, and the latter to the damping associated with lead-rubber isolators.

4.1. Fundamental mode shape of the model structures

Fig. 6 describes the fundamental mode shapes of the 5-story model structures both with and without base isolation obtained from eigenvlaue analysis. The mode shapes are normalized so that the modal displacements at the top story are the same in both cases. The natural period of each mode and the corresponding effective mass coefficients $\bar{\mu}_i$, defined in the following equation, are given in Table 4:

$$\mu_i=\frac{(\boldsymbol{\phi}_i^T\mathbf{Mr})^2}{\boldsymbol{\phi}_i^T\mathbf{M}\phi_i};\ \bar{\mu}_i=\frac{\mu_i}{\sum_j m_j} \tag{18}$$

where $\boldsymbol{\phi}$i is the ith mode vector, $\mathbf{M}$ is the mass matrix of the super-structure, $\mathbf{r}$ is the influence vector in which each element is unity, and m_j is the lumped mass of the jth story. These factors are independent of how the mode shape vectors are normalized. Compared with the fixed-based structure, the mode shape of the super-structure of the isolated one is close to a vertical line. Also it can be noticed that the effective mass coefficients of the given isolated buildings are higher than 99%, which indicates that the first mode dominates the dynamic behavior of the model structures.

Fig. 7 shows the fundamental mode shapes of the 5-story seismic isolated model structures obtained from the proposed method and the dynamic eigenvalue analysis. It can be seen that even though straight lines are used to predict the fundamental mode shapes in the proposed method, the mode shapes match well with those obtained from the eigenvalue analysis. This is especially true for the shear wall system.

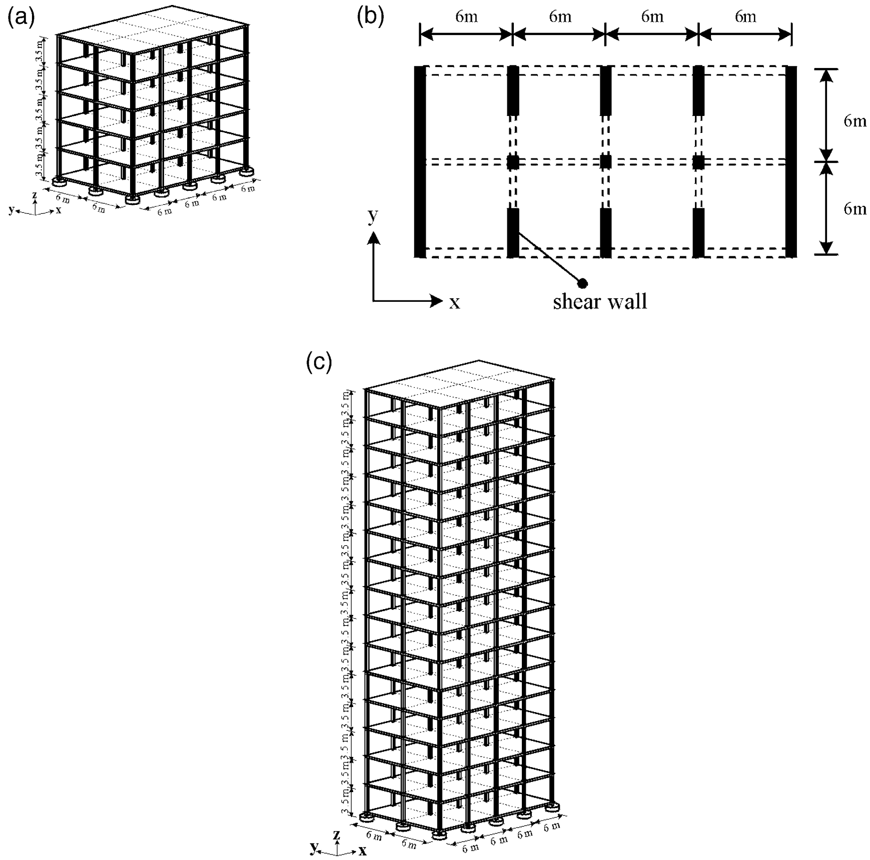

Fig. 5. Model structures with seismic isolation. (a) 5-story framed structure; (b) 5-story shear wall structure (plan); (c) 15-story structure.

Table 3
Design parameters of the model structures

	Period of isolation system, T_b (s)	Period of super-structure, T_s (s)	ε
Framed structure (5-story)	1.523	0.625	0.168
Shear wall structure	1.523	0.367	0.058
Framed structure (15-story)	3.501	1.426	0.166

4.2. Vertical distribution of seismic force in the 5-story structures

The model structures were first analyzed by time history direct integration method to obtain the vertical distribution of seismic force. For the dynamic analysis, two types of earthquake records, El Centro (NS) and Northridge records, were selected and were presented in Fig. 8. The Fourier transform of the records indicates that larger portion of vibration energy is distributed in the higher frequency range in the Northridge earthquake. As direct comparison of the base shear computed from the dynamic analysis and the static lateral response procedure is not appropriate, the peak ground acceleration of each vibration record was modified so that both records produce the same base shear with those obtained from the code procedures and the proposed method.

In Figs. 9–12 the results for vertical force distributions obtained from the proposed method and from UBC-91 and UBC-97 static lateral response procedures are compared with those computed by the dynamic time history analysis. The seismic zone factor and the site soil profiles were taken to be 2A and S_A, respectively. The spectral seismic coefficient C_{VD} and C_{AD}, which correspond to the constant velocity and acceleration regions of the DBE spectrum, respectively, and are functions of seismic zone factor and site soil profile type, were determined to be 0.12 for all the ground excitations. In the figures β is the isolator damping ratio and B and B_D are the damping coefficients defined in the codes.

Fig. 9 illustrates that for both ground excitations the slope of the vertical distribution of seismic force becomes larger in the order of UBC-97, proposed method, dynamic analysis, and UBC-91. Fig. 10 shows that the cumulative story shears obtained from UBC-91 and UBC-97 form lower and upper bounds, respectively. The difference between the two methods decreases as the damping in the isolators increases, but compared with the result of the dynamic analysis, the UBC-91 approach is basically unsafe. In contrast, UBC-97 procedure results in triangular distribution of seismic force

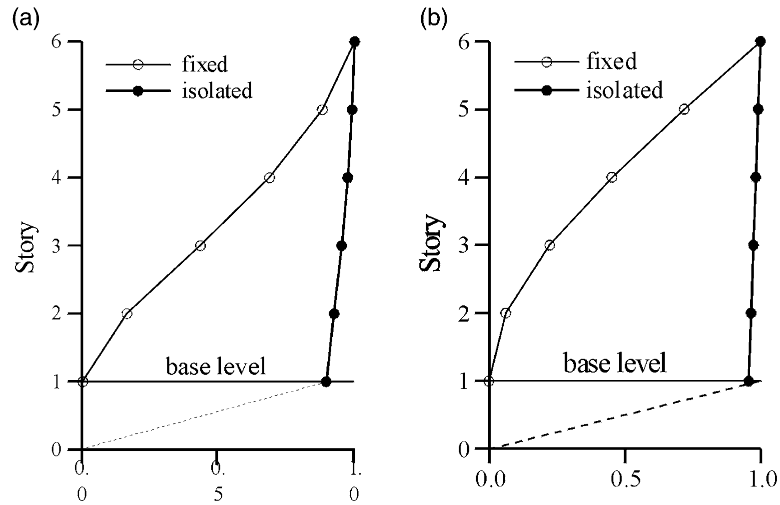

Fig. 6. Fundamental mode shapes for isolated and fixed-based structures. (a) Framed structure; (b) Shear wall structure.

Table 4
The natural periods and effective mass coefficient of the model structures

Mode (Y-dir)		1st	2nd	3rd
(a) 5-story framed structure				
Fixed-base structure	Period (s)	0.43	0.13	0.06
	Effective mass coefficient (%)	81.27	11.07	4.62
Seismic isolated structure	Period (s)	1.58	0.25	0.11
	Effective mass coefficient (%)	99.85	0.14	0.01
(b) Shear wall structure				
Fixed-base structure	Period (s)	0.07	0.01	0.00
	Effective mass coefficient (%)	67.07	20.53	7.26
Seismic isolated structure	Period (s)	1.54	0.16	0.01
	Effective mass coefficient (%)	99.97	0.02	0.00
(c) 15-story framed structure				
Fixed-base structure	Period (s)	1.40	0.41	0.12
	Effective mass coefficient (%)	74.00	11.39	5.07
Seismic isolated structure	Period (s)	3.72	0.79	0.35
	Effective mass coefficient (%)	99.39	0.58	0.03

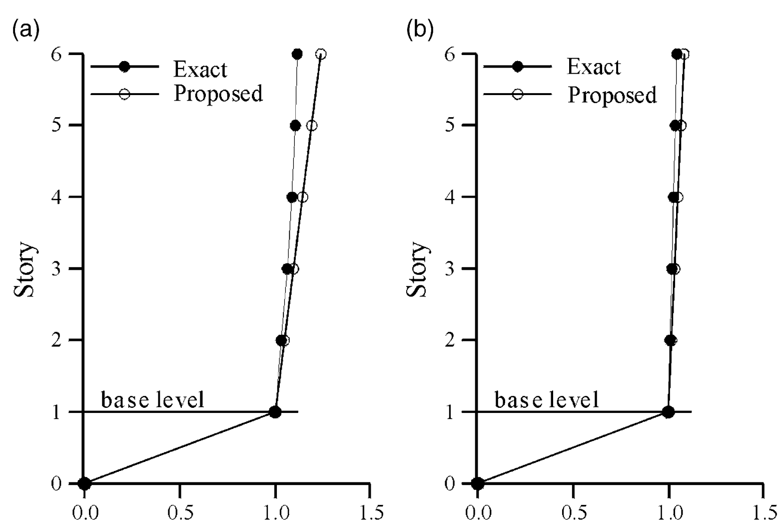

Fig. 7. Fundamental mode shapes obtained from the proposed method and the eigenvalue analysis. (a) Framed structure; (b) Shear wall structure.

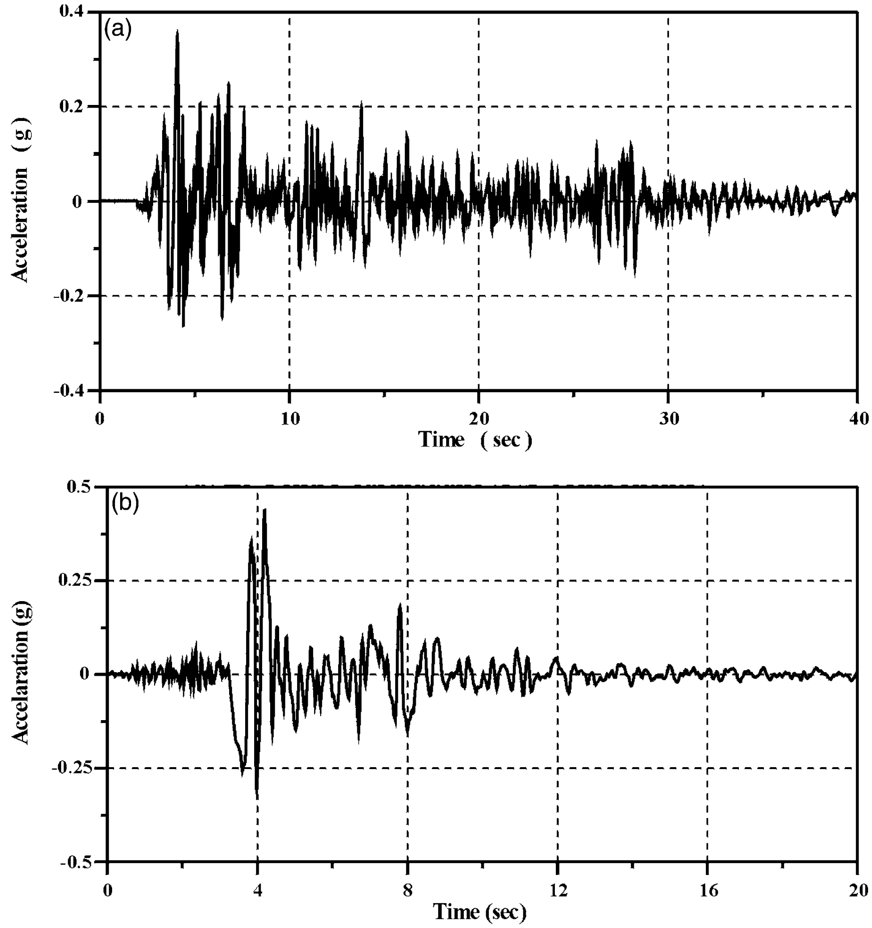

Fig. 8. Earthquake ground excitations used in the analysis. (a) El Centro earthquake (NS components); (b) Northridge earthquake (NS components).

similar to the case of the fixed-based structure, which is too conservative compared with the result of the dynamic analysis. This conservatism may have originated from the concern that the high damping in isolator increases the effect of higher modes and consequently the seismic load in the super-structure. This may be true for the system with isolators having high hysteretic energy dissipation capacity, such as lead-rubber isolators. However the present study verifies that for low-rise seismic isolated building structures with moderate linear isolator damping, the UBC-97 approach results in overestimation of the seismic story force. It also can be noticed that the distribution of the seismic story force produced by the proposed method is slightly more slanted toward the result from the UBC-97 than that from the dynamic analysis. This leads to the more conservative cumulative story shear than that obtained from dynamic analysis. These observations demonstrate that the proposed method provides more economic solution than the code procedure for the vertical distribution of the seismic force while still maintaining a margin for safety.

The same procedures were repeated for the shear wall structure, and the results were presented in Figs. 11 and 12. In this case the representative height of 0.5 h_n was used taking into account the dynamic characteristics of the structure. Compared with the results for framed structure, the vertical distribution of the story forces obtained from the dynamic analysis and the proposed structure are closer to the result of UBC-91, which is a vertical line. This seems to be natural considering the fact that as the shear wall structure is stiffer than the framed structure, it behaves more like a rigid body when isolated, which is the basic concept of the UBC-91 approach. Even in this case the story force and story shear distributions produced from the proposed method are slightly more conservative than those from dynamic analysis.

4.3. Effect of change in the effective height

The effective height, which was taken to be 0.7 and 0.6 h_n for shear wall and framed structures in this study, respectively, may vary slightly depending on mass distribution and structural systems (for their different deflected shapes). Fig. 13 shows the representative displacements and the corresponding effective heights of the 5-story model structures with their base fixed. The

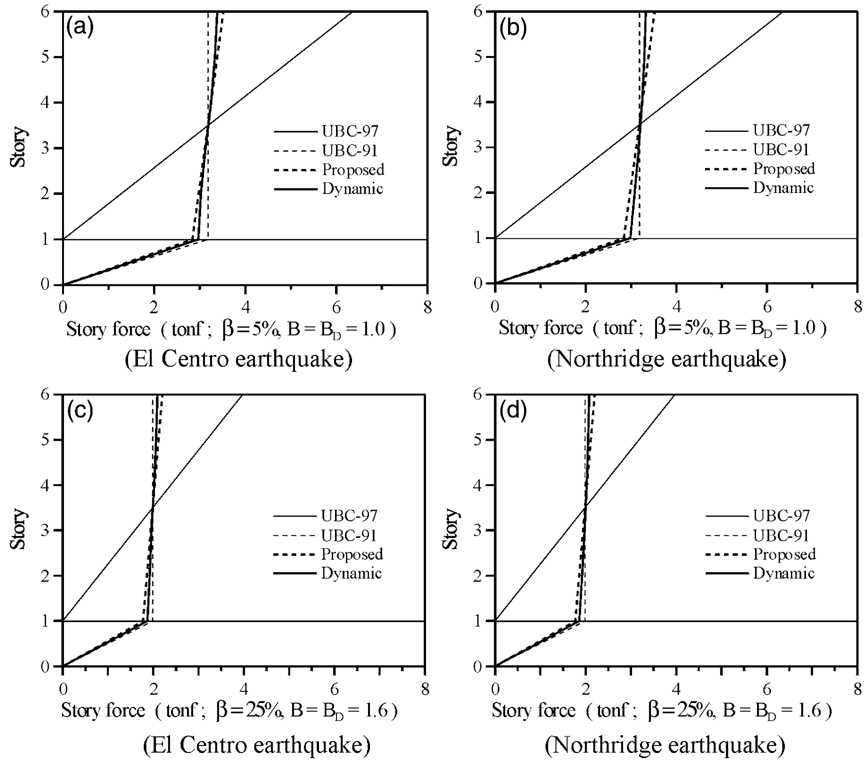

Fig. 9. Vertical distribution of seismic story force in 5-story framed structure. (a and b) Story force for 5% isolator damping; (c and d) story force for 25% isolator damping.

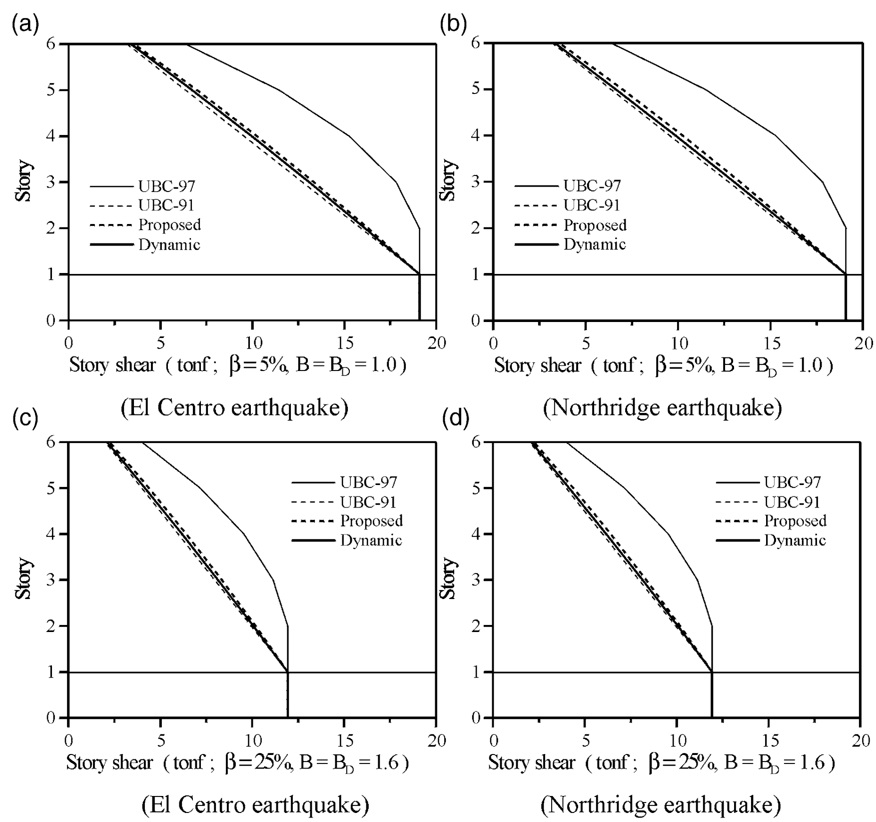

Fig. 10. Story shear in the 5-story framed structure. (a and b) Story shear for 5% isolator damping; (c and d) story shear for 25% isolator damping.

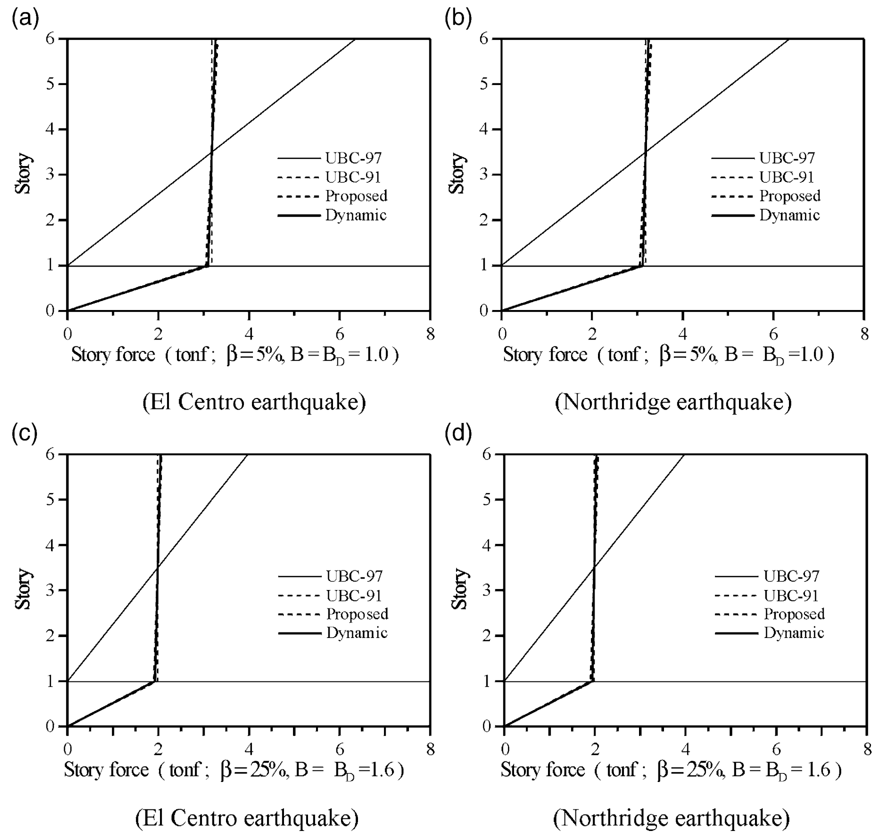

Fig. 11. Vertical distribution of seismic story force in the shear wall structure. (a and b) Story force for 5% isolator damping; (c and d) story force for 25% isolator damping.

representative displacements were computed using Eq. (16) with the maximum story displacements x_i computed from dynamic analysis with Northridge earthquakes. The effective heights of 0.8 and 0.68 h_n were obtained, which are a little higher than those recommended in the reference [12] and adopted in the proposed seismic load distribution procedure. The analysis with El Centro earthquake resulted in almost identical effective heights.

Figs. 14 and 15 compares the distribution of the story force and story shear in the 5-story framed and shear wall structures, respectively, obtained from the proposed process using two different values of the effective height, 0.7 and 0.5 h_n. The results from dynamic analysis with Northridge earthquake are also presented. The comparison of the results indicates that even though the difference is only marginal, the slope of the story force distribution decreases, i.e. the line is more inclined toward the horizontal axis, as the effective height decreases, which leads to more conservative distribution of story shear. Therefore the use of the recommended values seems to be adequate because they will provide more or less conservative results. For shear wall structures, where the seismic load distribution is almost identical to that obtained from dynamic analysis, even smaller value for effective height is recommended to ensure enough safety.

4.4. Vertical distribution of seismic force in the 15-story structure

For further investigation of the applicability of the proposed method, a 15-story framed structure was analyzed using the same earthquake records. Although in most design codes including the UBC and IBC the static lateral response procedure is not permitted for the structure as tall as this model, it would be instructive to examine the applicability of the static analysis procedure on a medium-rise structure. The design parameters used in the computation and the modal characteristics are listed in Tables 3 and 4, respectively. Figs. 16 and 17 describe the distributed seismic story force and story shear along the height, respectively. In this case the seismic force distributed over the height is highly nonlinear for both earthquake excitations, and the result obtained in accordance with the proposed procedure is not conservative, especially when the damping in isolators is small. This is due mainly to the strong participation of the higher modes. Therefore it can be concluded that the proposed static analysis procedure may not be applicable for medium to high-rise structures.

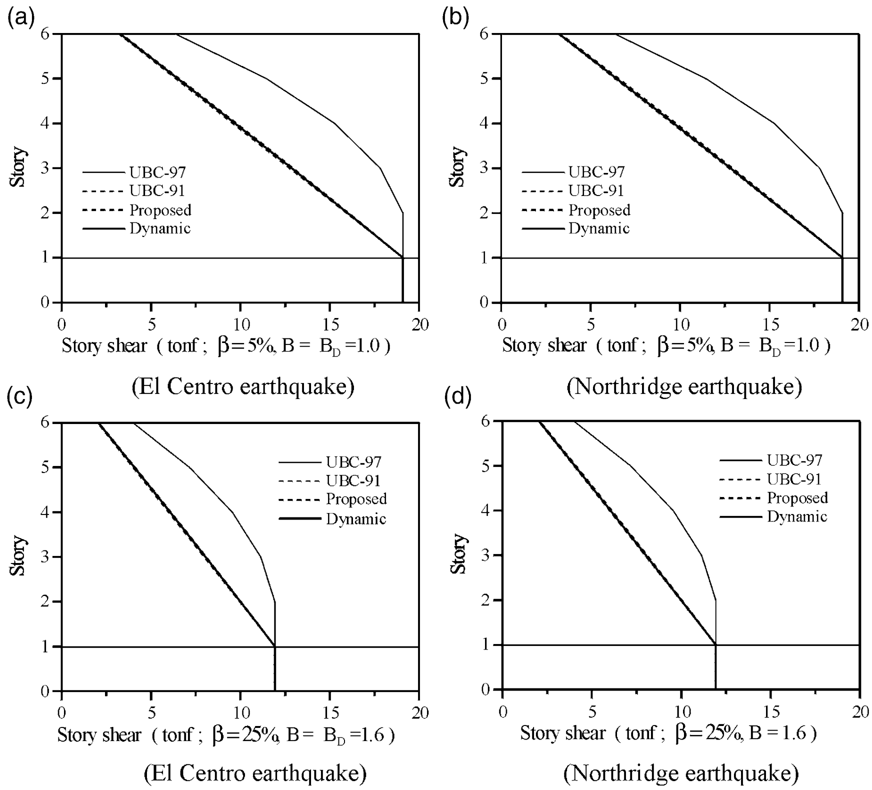

Fig. 12. Story shear in the shear wall structure. (a and b) Story shear for 5% isolator damping; (c and d) story shear for 25% isolator damping.

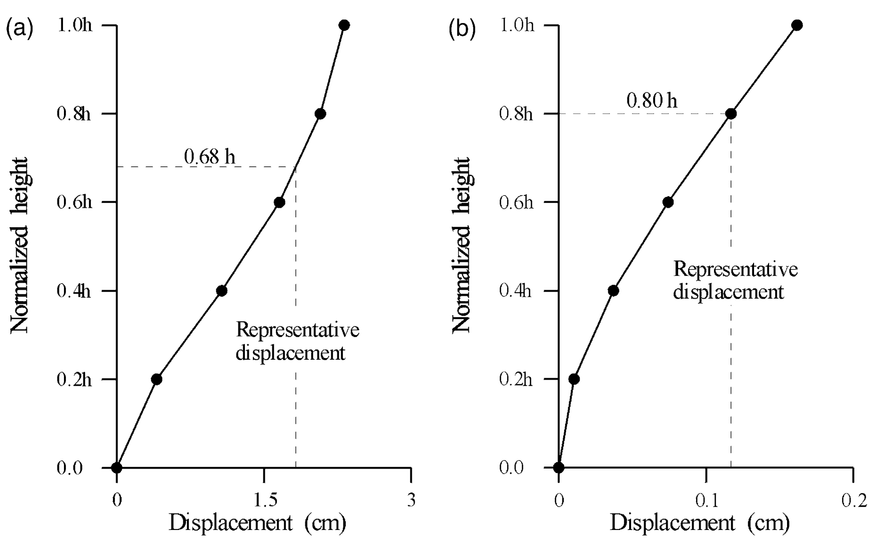

Fig. 13. Representative displacements and effective heights for fixed based model structures obtained from dynamic analysis. (a) Framed structure; (b) Shear wall structure.

5. Conclusions

In this study the validity of the seismic force distribution formulae for seismic isolated structures regulated in UBC-91 and 97 are investigated, and a modified formula is proposed based on a dynamics of two-mass linear system. As complicated analytical procedures are excluded, the proposed method is expected to be a convenient tool for evaluation of realistic seismic loads in preliminary analysis and design of a seismic isolated structure. It should be pointed out, however, that the application of the proposed formula is limited to a static analysis of a low-rise structure with linear isolators.

The following conclusions are drawn from the investigation of the seismic isolated 5-story framed and shear wall structures and a 15-story framed structure:

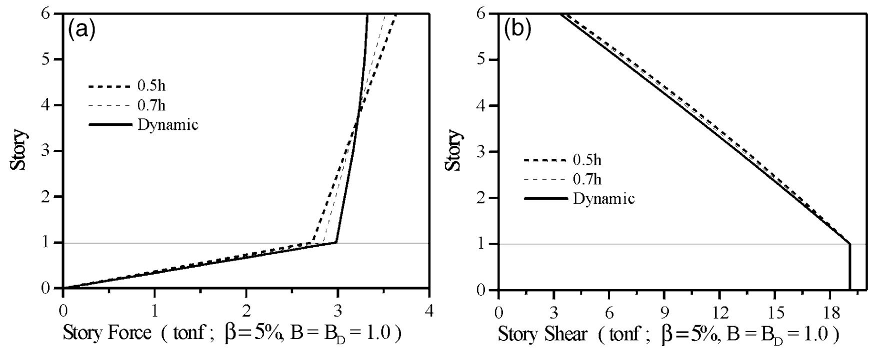

Fig. 14. Distribution of seismic load in the framed structure for different representative heights. (a) Variation of story force; (b) Variation of story shear.

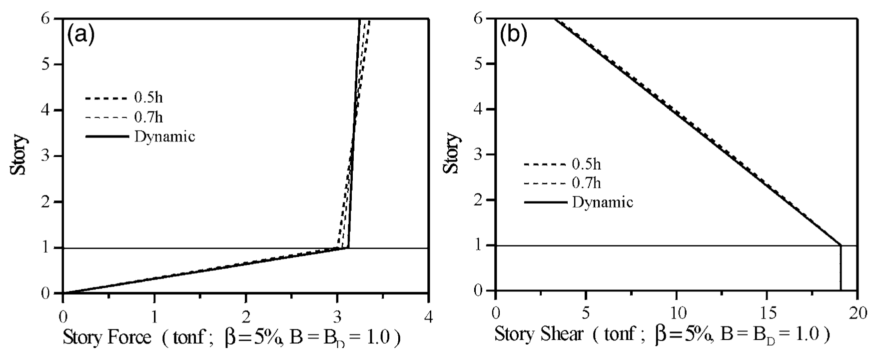

Fig. 15. Distribution of seismic load in the shear wall structure for different representative heights. (a) Variation of story force; (b) Variation of story shear.

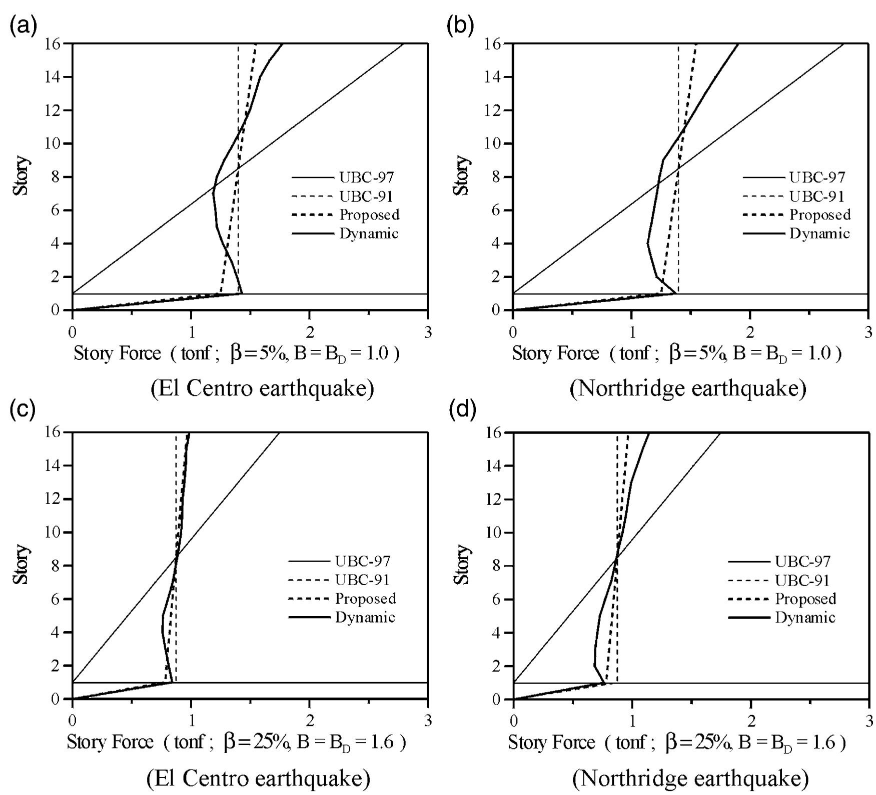

Fig. 16. Vertical distribution of seismic story force for the 15-story structure. (a and b) Story force for 5% isolator damping; (c and d) story force for 25% isolator damping.

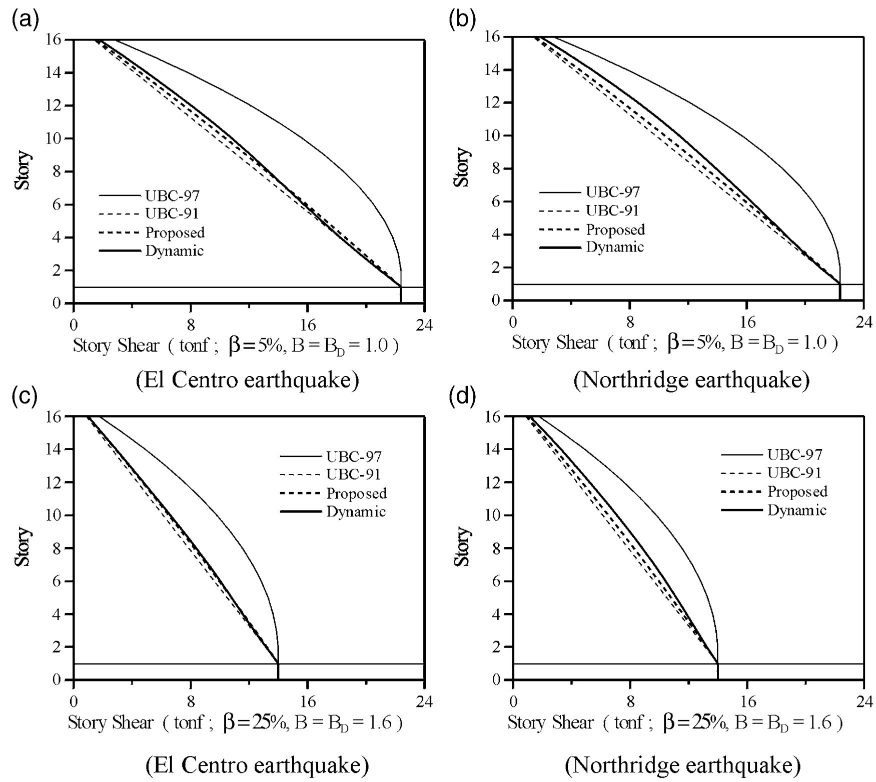

Fig. 17. Seismic story shear for the 15-story structure. (a and b) Story shear for 5% isolator damping; (c and d) story shear for 25% isolator damping.

1. The UBC-91, in which the super-structure is regarded as a rigid body and the seismic load is distributed in accordance with the story mass, may underestimate the seismic load due to the negligence of the effect of building height. On the other hand UBC-97 (and IBC-2000) disregarded the dynamic characteristics of the seismic isolated buildings and adopted the distribution formula for fixed-based structure, resulting in too conservative results compared with those of dynamic analysis.
2. The proposed formula provides slightly conservative seismic story force compared with the results from dynamic analysis, and results in a more economic design compared with the procedure of the UBC-97 and the codes based on the same idea such as IBC-2000.
3. The proposed method and the code specified static lateral response procedure cannot be applicable for medium or high-rise structures in which the effect of the higher modes is not negligible.

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