A NEW DISPLACEMENT-BASED SEISMIC DESIGN METHOD FOR SHEAR WALL STRUCTURES

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ABSTRACT: According to the characteristics of shear wall structures, the destructive story drift ratio is employed to represent the performance index of structures. Then, the performance levels of shear wall structures are quantified and the lateral deformation is controlled by two parameters of destructive story drift ratio and roof drift ratio. Based on the seismic fortification level in Chinese Code for Seismic Design of Buildings, the performance of shear wall structures is divided into three levels: fully operational, performance interruption and collapse prevention. Applying the inverted triangular distribution of lateral force to the cantilever wall with identical section, the displaced curve is regarded as the initial lateral displacement mode. By employing the design parameter of destructive story drift ratio, the determining method of target lateral displacement for shear wall structures is demonstrated and a destructive story drift-based seismic design method is presented. In the "fully operational" performance level, the target lateral displacement is determined by the corresponding drift curve when the shear wall structure reaches the target destructive story drift ratio. Afterward, the equivalent parameters of single-degree-of-freedom system can be calculated, and the base shear and horizontal earthquake action of every mass of multi-degree-of-freedom system can be estimated. In the "performance interrupt" and "collapse prevention" performance levels, the designed structure is adjusted based on the relationship between pushover curve and demand curve and the ductility demands of structure. It is demonstrated the method in this paper is convenient for practical application, which can be employed to control the performance of shear wall structures under different earthquake levels.

KEYWORDS: shear wall structure, displacement-based seismic design, performance level, effective parameter

1. INTRODUCTION

Reinforced concrete shear walls have always been recognized for their large lateral stiffness and strength, which provide for good control over horizontal displacements and story drifts. Thus, reinforce concrete structural walls are commonly used in tall buildings for resisting lateral forces imposed by wind or earthquakes. The two stages seismic design method is adopted for shear wall structures in the Chinese Code for Seismic Design of Buildings (CCSDB, GB 50011-2001) and other design codes. In the first stage, it is necessary to calculate the earthquake action and seismic action effect of building structures under minor but frequently occurring earthquakes, combine it with gravity load effect, and check the bearing capacity of the shear wall section based on the combined internal force of critical section of members. In the second stage, the designer proceeds to the elastoplastic deformation checking computations for the structure under rare but major earthquakes. This procedure is a force-based seismic design method, i.e., the force is regarded as the design parameter at the beginning.

Earthquake damage analysis and experimental results have shown that the force-based seismic design method mentioned above can ensure that buildings resist minor earthquakes without damage and undergo major earthquakes without collapse. However, in the 1990s, the earthquakes occurring in metropolis of developed countries brought few earthquake casualties, but resulted in tremendous economic losses for the buildings invested heavily in equipment and decoration because of excessive structural damage, although they didn't collapse. Thus, the researchers are aware that simply emphasizing that the structure is not severely damaged and collapsed under the earthquake action is not a perfect seismic design concept and can not satisfy the demand of seismic design of modern engineering structures. Under this background, the scholars of America and Japan put forward the idea of performance-based seismic design. In recent years, much progress has been made on the approach of performance-based seismic design (Medhekar *et al*. 2000), and the method has been partially adopted by the modern seismic design codes in many counties.

Experimental investigations show that the performance of engineering structures in each stage is closely related to the deformation capacity, that is, the quantificational relationship between structural performance and deformation index can be established. Hence, the displacement is regarded as the design parameter in performance-based seismic design, and then, the displacement-based seismic design approach (Kowalsky *et al*. 1995, 2001; Priestly *et al*. 2000, Medhekar *et al*. 2000) is presented. In this paper, a new displacement-based design method for shear wall structure is presented.

There are two basic problems in displacement-based design for shear wall structure. Firstly, it is necessary to determine the corresponding target drift curve based on the performance objectives of structure, calculate the base shear and the horizontal earthquake force at each floor, and check the bearing capacity of the shear wall section. Secondly, according to the deformation demand of structure under a certain intensity of earthquake action, it should proceed to the deformation capacity design of shear wall section, and ensure that the structure is able to reach the prospective performance objective. Only the first problem will be analyzed and studied in this paper.

2. THE PERFOMANCE LEVELS AND QUANTIFICATION OF SHEAR WALL STRUCTURE

In displacement-based seismic design, the relationship between performance level and target displacement should be determined. In order to correspond with the earthquake fortification objective in CCSDB and control the deformation behavior of a structure, the performance level of building structures is divided into three: fully operational, performance interruption, and collapse prevention in this paper. In a certain levels of ground motions, these three performance levels are consistent with the specified level of without damage, repairable and without collapse in CCSDB, respectively. But in CCSDB, seismic design has been carried out based on the philosophy that buildings should be able to resist minor earthquakes without damage, should continue to function with repairable damage when subject to moderate earthquakes, and should not collapse when subject to major earthquakes. Thus, this is a performance-based earthquake fortification objective, which ensures the safety of the occupants of structure. However, in performance-based seismic design, various seismic fortification criterion, such as without damage to structure when subject to moderate or major earthquakes, can be adopted according to the importance of the building and the requirement of the owner. It is different from the traditional seismic design methods.

It has been recognized that the story drift ratio of a multi-story building, defined as the ratio of the story drift to the story height, reflects the total deformation of members in the story for reinforced concrete structure and can be a good measure of structural and nonstructural damage of the building under various levels of ground motions. Thus, the performance levels can be qualified by story drift ratio in performance-based seismic design procedure.

Researches by the present author (Deng 2006) show that the story drift ratio in shear wall structures can be divided into the destructive story drift ratio and the nondestructive story drift ratio. The destructive story drift ratio reflects the force-induced deformation and relates to the structural performance levels; the nondestructive story drift ratio, produced by the rigid body rotation of the floor, only relates to the serviceability limit state.

In this paper, according to the characteristics of shear wall structures, the destructive story drift ratio is employed to represent the performance index of structures, and the story deformation of shear wall structures are controlled by two parameters of the destructive story drift ratio and roof drift ratio. The destructive story drift ratio controls the force-induced deformation in the lowers stories and the roof drift ratio controls the rigid body rotation of floors in the upper stories to satisfy the requirements of serviceability and to reduce the P-delta effects under gravity loads. Based on extensive experimental investigations (Liang 2007), the destructive story drift ratio limits of shear wall structure corresponding to the three performance levels can be given as follows: in the serviceability performance level, taking $[\theta]=1/1000$; in the life safety performance level, taking $[\theta]=1/250$; in the collapse prevention performance level, taking $[\theta]=1/100$.

3. THE TARGET LATERAL DISPLACEMENT OF SHEAR WALL STRUCTURES

3.1. The Initial Lateral Displacement Mode of Shear Wall Structures

In direct displacement-based seismic design, the lateral displacement mode of the structure should be determined at the first step. Next, the corresponding target drift curve for the structure can be obtained according to the performance objective. Then, the equivalent parameter and base shear can be calculated. For shear wall structure, applying the inverted triangular distribution of lateral force to the cantilever wall with identical section, as shown in Figure 1, the displaced shape can be regarded as the initial lateral displacement mode. That is,

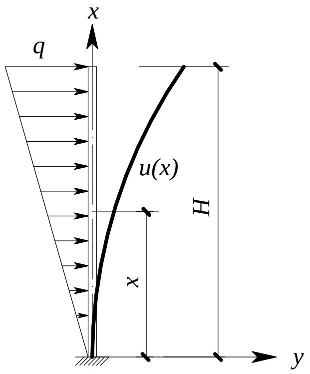

Figure 1 The initial lateral displacement mode

$$u(\xi)=\frac{\phi H^2}{40}(20\xi^2-10\xi^3+\xi^5) \tag{1}$$

where ϕ denotes the curvature at the bottom critical section of the first story of shear wall structure, H denotes total height of the building, and ξ is the height ratio of storey, which is expressed as $\xi=z/H$.

In fully operational performance level, assuming that the curvature at the bottom critical section of the first story of the shear wall structure reaches yield value, which is in correspondence to the elastic limit state, the corresponding target drift curve is expressed as

$$u(\xi)=\frac{\phi_y H^2}{40}(20\xi^2-10\xi^3+\xi^5) \tag{2}$$

where ϕ_y denotes the yield curvature of the section, which can be determined as (Kowalsky *et al*. 2001)

$$\phi_y=2\varepsilon_y/h_w \tag{3}$$

in which ε_y is the yield strain of the longitudinal reinforcement at the end of shear wall section, and h_w is the depth of section.

3.2. The Target Story Drifts and Floor Displacement of Shear Wall Structures

According to the characteristic of shear wall structures, when the destructive story drift is regarded as the performance index, the target story drifts and floor displacement can be calculated in the following procedures.

(1) Select a specific destructive story drift ratio and regard it as the target destructive story drift ratio according to the performance level of structure. Such as, for 'fully operational' performance level, giving $\tilde{\theta}$=1/1000.

(2) Determine the special target story where the maximum force-induced deformation will be reached by the elasticity analysis, and calculate the floor rotation of the corresponding story. Usually, the special target story occurs in the several stories close to the base.

(3) Assume that the special target story reaches the target destructive story drift ratio, and then calculate its destructive story drift.

(4) According to the relationship between the nominal story drift and destructive story drift (Deng, 2006), calculate the nominal story drift of the special target story, which can be regarded as the target story drift under the corresponding performance level.

(5) Calculate the curvature at the bottom critical section of the first story of shear wall structure, and then c

ompute the roof displacement based on the dimensionless floor height ratio ξ and the lateral drift curve of shear wall structure in equation (1).

(6) Lastly check the roof displacement ratio. If it satisfies the allowable upper limit, the floor displacements of a shear wall structure under a certain performance level can be determined. If it does not satisfy the requirement for roof displacement ratio, modify the value of the target destructive story drifts ratio, and recalculate the floor displacement and roof displacement until it is satisfied.

4. DISPLACEMENT RESPONSE SPECTRA

In a traditional force-based design, the period of natural vibration of a structure is estimated based on previous trial design, and design pseudo-acceleration response spectra are entered to determine the elastic design force level on the structure. However, in displacement-based seismic design, the required design displacement demand for the structure can be specified, and the displacement response spectra can be used to determine the required period of vibration, provided that the structure has been modeled assuming a linear behavior and a viscous damping equivalent to the actual non-linear response. Hence, the displacement response spectra, for a given level of damping, are the basis of direct displacement-based seismic design. The smoothed elastic response spectra can be determined by two methods:

(1) Based on large numbers of strong ground motion record (or earthquake wave), the relationship between the period of vibration of a structure T and the spectral displacement S_d can be obtained by numerical integration.

(2) Based on the design pseudo-acceleration response spectra $S_a(T)$ in CCSDB, the displacement response spectra can be expressed as

$$S_d = \left(\frac{T}{2\pi}\right)^2 S_a \tag{4}$$

It has to be pointed out, however, that the spectral pseudo-accelerations is magnified for moderate or long period structures in order to avoid that the earthquake action of the structure is too small. Thus, the displacement response spectra obtained from equation (4) will be different from the real displacement response for moderate or long period structures. Whereas, the difference of period for shear wall structure can be decreased because the corresponding spectral acceleration fall into the range of short or moderate period structures. Consequently, on the condition of without displacement response spectra in accordance with the fact, the design spectra for displacement can be determined by equation (4) to calculate the earthquake displacement response of shear wall structure.

Based on the smoothed acceleration response spectra in CCSDB, from equation (4), we obtain the period of vibration expressed as

$$T^2[0.45+10(\eta_2-0.45)T] = \frac{4\pi^2}{\alpha_{\max} g} S_d \qquad (T \le 0.1s) \tag{5a}$$

$$T = 2\pi\sqrt{\frac{S_d}{\eta_2 \alpha_{\max} g}} \qquad (0.1s \le T \le T_g) \tag{5b}$$

$$T = \left(\frac{4\pi^2}{T_g^\gamma} \cdot \frac{S_d}{\eta_2 \alpha_{\max} g}\right)^{\frac{1}{2-\gamma}} \qquad (T_g \le T \le 5T_g) \tag{5c}$$

$$T^2\left[0.2^\gamma \eta_2 - \eta_1\left(T-5T_g\right)\right] = \frac{4\pi^2}{\alpha_{\max} g} S_d \qquad (5T_g \le T \le 6.0s) \tag{5d}$$

$$\gamma = 0.9 + \frac{0.05-\zeta}{0.5+5\zeta}, \qquad \eta_1 = 0.02 + \frac{0.05-\zeta}{8}, \qquad \eta_2 = 1 + \frac{0.05-\zeta}{0.06+1.7\zeta}$$

where $\alpha_{\max}$ denotes the maximum value of horizontal seismic influence coefficient. For frequent, low-intensity and infrequent severe ground motions, it can be obtained from current seismic design code. For moderate ground motion, taking $\alpha_{\max}$ =0.23, 0.45 and 0.90 when the earthquake fortification intensity is Ⅶ, Ⅷ and Ⅸ, respectively.

When the equivalent displacement u_{eff}, which is equivalent to S_d in equation (5), is obtained, the parameters, such as seismic fortification level, site classification, damping ratio and so on, are determined. Then, the corresponding effective period can be calculated by equation (5).

5. DESTRUCTIVE STORY DRIFT-BASED DESIGN APPROACH FOR SHEAR WALL STRUCTURES

In this paper, according to the characteristic of shear wall structures, the destructive story drift is regarded as the performance index and a new displacement-based design procedure is outlined as follows.

5.1. Design Procedure According to Fully Operational Performance Level

(1) Preliminary design of the structure, including selection of concrete and reinforcement grades and determination of member size of shear wall.

(2) Based on the significance of the structure and the requirement of owner, determine the performance objective, i.e., “fully operational under minor earthquakes and collapse prevention under major earthquakes” or “fully operational under moderate earthquakes and performance interruption”. And designate the destructive story drift ratio as the performance index.

(3) Select the corresponding allowable value of destructive story drift ratio, specify the special target story where the maximum force-induced deformation will be reached by the elastic analysis, and determine the target displacement pattern of shear wall structure based on equation (2). Then, calculate the story drift ratio in each story and satisfy $\theta_i \le [\theta]$.

(4) Calculate the floor displacement at each floor from previous steps, and determine the effective displacement u_{eff} and effective mass M_{eff} of the equivalent single-degree-of-freedom system from equations in the following.

$$u_{eff} = \frac{\sum_{i=1}^{n} m_i u_i^2}{\sum_{i=1}^{n} m_i u_i} \tag{6}$$

$$M_{eff} = \frac{\sum_{i=1}^{n} m_i u_i}{u_{eff}} \tag{7}$$

where m_i denotes the mass at each floor.

(5) According to the seismic fortification level, effective damping ratio ζ_{eff} and effective displacement u_{eff}, determine the effective period T_{eff} from equation (5), in which the effective damping ratio ζ_{eff} is given by (Miranda *et al*. 2002)

$$\zeta_{eff} = \zeta_0 + 0.2(1 - 1/\sqrt{u}) \tag{8}$$

where ζ_0 represents the viscous damping ratio in elastic system, which can be given as 0.05 for reinforced concrete structure, μ denotes the displacement ductility demand, which can be determined by the seismic fortification level. For example, under a certain level of ground motion, give $\mu = 1.0$ for serviceability performance level and $\mu = 3.0 \sim 4.0$ for collapse prevention performance level, and so on.

(6) Determine the effective stiffness K_{eff} of the equivalent single-degree-of-freedom system, the base shear V_b of the structure and the horizontal earthquake action F_i at each story level, namely,

$$K_{eff} = \left(\frac{2\pi}{T_{eff}}\right)^2 M_{eff} \tag{9}$$

$$V_b = K_{eff} \cdot u_{eff} \tag{10}$$

$$F_i = \frac{m_i u_i}{\sum_{j=1}^{n} m_j u_j} V_b \tag{11}$$

(7) Calculate the horizontal earthquake action effect and corresponding gravity load effect of the structure. Then, check the bearing capacity of shear wall section and adopt the details of seismic design.

(8) The designed structure is analyzed with pushover method. If the pushover drift curve, corresponding to the special target story of the shear wall structure reaches the target destructive story drift, is identical with the initial assumed shape, the design is valid. Otherwise, the corresponding pushover drift curve when the special target story of the shear wall structure reaches the target destructive story drift can be employed as the modified target lateral displacement curve, and then, recalculate the base shear and horizontal earthquake action, and check the bearing capacity of shear wall section until it is satisfied, based on the method mentioned above.

Based on the method presented above, if the structure is required to satisfy the serviceability performance level when subject to minor but frequently occurring earthquakes, from equation (5), the effective period can be determined based on the corresponding ground motion parameter. Then, other design parameters and horizontal earthquake action can be obtained from equations (6) to (11). Similarly, if it is required to satisfy the serviceability performance level when subject to moderate or rare but major earthquakes, the effective period can be determined according to the corresponding ground motion parameter of moderate or major. Then, the other design parameters can be determined from equations (6) to (11).

5.2. Performance Interruption and Collapse Prevention Performance Level

Under the frequently occurred earthquake action, the structure is required to satisfy the serviceability performance level. Furthermore, the displacement of the structure should be controlled in the life-safety and collapse prevention performance level.

These two performance levels are in correspondence to the performance of building structure under moderate intensity earthquake and seldomly occurred earthquake. Under the action of seldomly occurred earthquake, assume that the curvature at the bottom cross section of shear wall reaches the ultimate curvature ϕ_u. The corresponding target lateral displacement mode can be determined from equation (1) and the story drift ratio θ_i can be obtained. Ensure that θ_i satisfies the allowable value, namely, $\theta_i \le [\theta]$. Then, the corresponding displacement u and base shear V_b can be obtained from equation (6) and (10). Under the action of moderate earthquake, assume that the curvature at the bottom cross section of shear wall reaches $\phi_u/2$. Similarly, the corresponding displacement u and base shear V_b can be calculated.

Finally, the base shear and displacement corresponding to the three performance levels can be drew in a same $V-u$ coordinate, such as point A, B and C in Figure 2. By linking these points, the base shear versus displacement curve represents the demand curve under serviceability, life-safety and collapse prevention performance level.

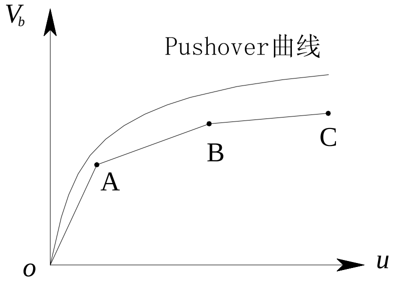

Figure 2. The demand curve and pushover curve

Afterward, the designed structure is analyzed with nonlinear static procedure. Place the pushover curve and demand curve on a same coordinate, as shown in Figure 2. According to the relationship between demand curve and pushover curve, the design result can be modified by the following method.

(1) If the pushover curve is consistent with or above the demand curve, as shown in Figure 3a, the designed

structure satisfies the performance levels.

(2) If the pushover curve is below the demand curve, as shown in Figure 3b, the designed structure does not satisfy the performance levels and should be redesigned.

(3) If point B is lower than point A in the demand curve, as shown in Figure 3c, it is indicated that the seismic demands in moderate earthquake is too low. Then, the earthquake resistant demand should be improved.

(4) If point B is much higher than point A in the demand curve, as shown in Figure 3d, two problems may be exist in the designed structure as follows.

1) The initial stiffness of the structure is too small. The size of the structure member should be adjusted and the initial stiffness needs to increase in appropriate range.

2) The performance demand for moderate earthquake is too high and should be decreased.

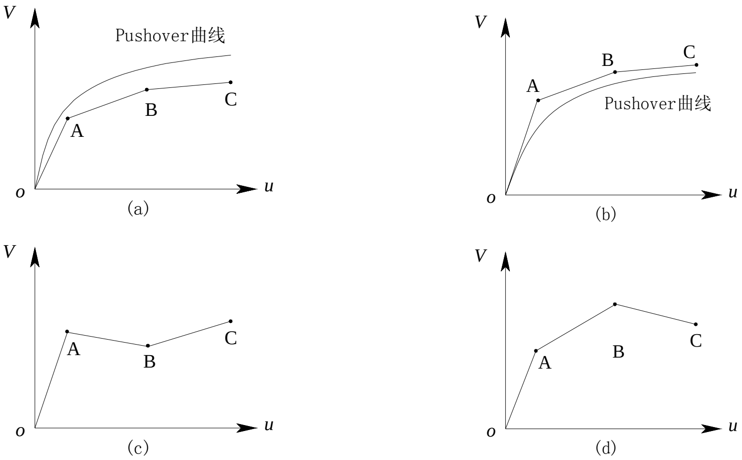

Figure 3. Several demand curve and pushover curve

Based on the displacement demand of the moderate and major earthquakes, the corresponding pushover drift curve can be obtained. Consequently, the damage information and plastic hinge distribution under these two conditions can be obtained. Then, the local reinforcement of the structure can be adjusted according to the information.

6. CONCLUSIONS

Above all, the characteristic of the method in this paper is listed as follows:

(1) According to the characteristics and lateral displacement of shear wall structures, the use of destructive story drift ratio to specify the performance index and to quantify the structural performance levels is well correlated with story deformation and damage control in shear wall structures.

(2) The plastic hinge of shear wall structure formed at the bottom. Thus, the target lateral displacement curve is determined by destructive story drift ratio at maximum force-induce story, which reflects the fact that the critical section of the structure reaches a certain limit state firstly.

(3) When determine the initial lateral displacement curve, the shear wall structure is regarded as a cantilever wall with identical section. Perhaps it is not in accordance with the fact. The modified lateral displacement curve, which is obtained from the pushover drift curve corresponding to the state that the special target story of the shear wall structure reaches the target destructive story drift, reflects the change of strength and stiffness over the height of the structure.

(4) Based on the procedure in this paper, the performance of the structure is controlled under not only minor and major earthquakes, but also moderate earthquakes. This is the objective that should be achieved in performance-based seismic design.

7. ACKNOWLEDGEMENT

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