Yield Mechanism-Based Performance Design of Coupled Shear Walls

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***Abstract* — Seismic performance control of coupled shear walls is one of the issues not yet resolved well. Based on the idea of yield mechanism control of coupled shear walls and performance design, a method based on the best mechanism of coupled shear walls is proposed. First, yield mechanism and target drift under the given earthquake level is selected, and the design base shear is calculated by equating energy equation, and a lateral design force distribution consistent with the intended yield mechanism is calculated. The shear force and required plastic moment of the coupling beams are determined by the coupling ratio. Finally, in order to achieve the intended mechanism and performance, the required plastic moment of wall piers in the first story is determined by using the energy balance equation under the intended yield mechanism. A 12 layers coupled shear wall is designed using this method, and comparison with elsto-plastic time-history analysis shows the obtained results are reliable, and comparison with the frequent earthquake elastic design result shows that coupled shear walls' design results using actual standard is slightly lower than the performance request of no collapsing with strong earthquake.**

Keywords - coupled shear walls; yield mechanism; performance design theory; target drift; coupling ratio

I. INTRODUCTION

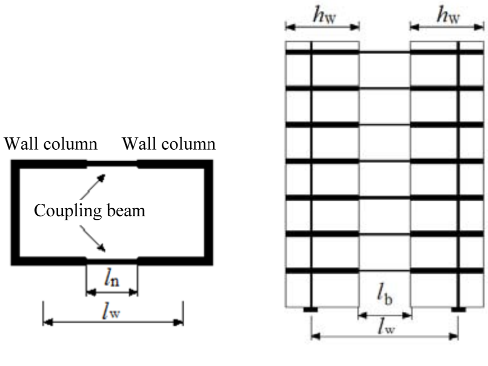
Coupled shear wall is the lateral resisting structure consisting of several wall columns connected together through coupling beam. With the horizontal axial force and vertical shear force created by lateral force, the transmission of coupling beam among wall columns may resist a part of capsizing moment, so that the bending moment of wall column is reduced. A part of earthquake energy of the structure of coupled shear wall is input into the coupling beam through its inelastic deformation dissipation. What is particularly important is that the lateral rigidity of coupled shear wall is much larger than the sum of that of each independent wall column, which is a kind of effective lateral resisting structure and widely used in multi-storey and tall building structures. From the view of structural analysis and coordination idea of section design, the method of structural analysis may directly take the inelastic performance of structure into consideration. Based on the earthquake resistant design method of structure performance, the control for structural performance may directly be made, and its basic idea is to make the engineering structure designed meet requirements of various kinds of intended performance objectives during application period [14], which has been recommended by Chinese specifications [1-2]. Sahoo D. R et al. [15] have proposed the plastic design method of steel braced frame structure based on performance. This method may directly consider the inelastic performance of the structure and have no demands for evaluation and iteration with clear concept and simple calculation, which is beneficial to the popularization and application in the practical design process. Based on this, this paper proposes the performance design method of structure of coupled shear wall based on the yield mechanism. This method firstly confirms the yield mechanism of structure of coupled shear wall in the seismic performance objective D [1]; adopts the energy-balance equation to obtain the design base shear in respectively accordance with the ground motion parameters of earthquake with design intensity and earthquake with estimated rare intensity and corresponding lateral fleet angle limits, and the greater among them shall be regarded as the design basis. Then, the coupling beam and the lower section at the base storey of wall column adopt plastic method for design, while the remaining sections of wall column adopt elastic method for design.

II. CALCULATION DIAGRAM AND YIELD MACHANISM OF COUPLED SHEAR WALL

To easily analyze the internal force of coupled shear wall, for the coupled wall shown in Fig.1(a), it can be simplified as the diagram shown in Fig.1(b). Among them, the coupling beam is simplified as the beam element and the bending deformation and shear deformation shall be considered. Wall column uses the beam-column element located in centroidal axis for expression, and for the column, the bending, axial direction and shear deformation shall be taken into consideration. At the elevation of each story, the rigid link for denoting the actual size of wall column is set up. In Fig.1, l_w denotes the distance of cardiac axis between two wall columns; h_w denotes the depth of section of wall column; l_b denotes the calculated span. The value shall be taken according to the following formula:

$$l_b = l_n + h_b / 2 \quad (1)$$

In the formula, l_n denotes the net span of coupling beam; h_b denotes the depth of section of coupling beam.



(a) (b)

Figure 1. Model for coupled shear walls

Under the effect of strong shock, the optimum yield mechanism of coupled shear wall dominated by the reaction of basis vibration mode shall be that: in the height of the whole structure, the coupling beam is successively yielded. Finally, the wall column is formed into plastic hinge at the basic top face to reach the ultimate limit state [16], which is shown in Fig.2. Coupling beam is yielded before wall column and then dissipates the earthquake energy, which may reduce damages resulted from large lateral displacement generated of the system because the plastic hinge appears in the wall column. To make coupling beam fully dissipate the earthquake energy, the coupled shear wall must have appropriate coupling rate, so that the coupling beam has sufficient carrying capacity, rigidity and deformability, and the adequate and stable hysteretic response may be realized through the expected inelastic deformation.

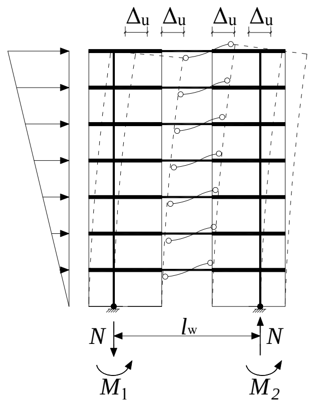


Figure 2. Yield mechanism of coupled walls

For the coupled shear wall, the moment equilibrium conditions at the base include:

$$M_0 = M_1 + M_2 + Nl_w \tag{2}$$

In the formula, *M*0 is the total capsizing moment at the bottom of structure; *M*1 and *M*2 are respectively the bending moments born by wall columns 1 and 2; *N* is the axial force of wall column; l_w denotes the distance of centroidal axis between two wall columns.

Define the coupling rate CR of coupled shear wall as:

$$CR = Nl_w / M_0 \tag{3}$$

Coupling rate reflects the influence of strength and rigidity of coupling beam on stress performance of coupled shear wall. For New Zealand Suggestions of Specification of Concrete Structure [17], if the displacement ductility factor of coupled shear wall needs to meet $5 \le \mu_\Delta \le 6$, the coupling rate CR of coupled shear wall shall be $1/3 \le CR \le 2/3$. Select the targeted coupling rate CR, and confirm the total shear force undertaken by all coupling beams:

$$\sum_{i=1}^{n} V_{bi} = \frac{CR \times M_0}{l_w} \tag{4}$$

In the formula, $\sum_{i=1}^{n} V_{bi}$ denotes the value of shear force undertaken by all coupling beams.

For the coupled shear wall taking the reaction of basic vibration mode as the leading, the formula (4) is the necessary condition to guarantee the yield mechanism formed shown in Fig.2.

III. PERFORMANCE DESIGN METHOD BASED ON YIELD MECHANISM

A. Energy-balance Equation and Correction Factor

Energy equation of elastic-plastic system may be written as:

$$E_e + E_p = E \tag{5}$$

In the formula, *E* denotes the input earthquake energy; E_e and E_p are respectively the elastic component and plastic component of energy required for targeted lateral displacement of structure realized (including hysteretic energy dissipation).

Researches show that [19] the input earthquake energy E calculated by formula (5) has great difference from the physical condition because of plastic deformation of the structure and some other reasons. Simultaneously, in consideration of over-conservative result of damping dissipation energy designed according to formula (5), the right-hand member of equation (5) shall be multiplied by energy correction factor γ . In addition, for concrete shear wall and other structures, because of the rheostriction resulted from degraded hysteretic performance and rebar bond slip, the energy-dissipating capacity is weakened under the severe earthquake action, and the force-deformation hysteretic curve has obvious rheostriction. Because the difference of hysteretic characteristics of different structures only has great influence on inelastic strain energy E_p but no

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obvious influence on elastic vibration energy E_e and input earthquake energy E, the reduction factor η is introduced to correct the inelastic strain energy E_p. Therefore, the formula (5) can be turned into:

$$E_e + \eta E_p = \gamma E \tag{6}$$

In the formula, γ is the correction factor of input earthquake energy; η is the energy reduction factor for considering structural strength and rigidity.

Correction factor γ of input earthquake energy mainly depends on ductility factor μ_Δ and ductility reduction factor R_μ of the structure [20]. Fig.3 shows the relationship between structural force and deformation. In the figure, OAB line is the force-deformation relationship of ideal elastic plastic of concrete coupled shear wall, while OAG line denotes the force-deformation relationship of corresponding ideal elastic plastic system. Therefore, from Fig.3, it can be obtained that:

$$\gamma\left(\frac{1}{2}V_e\Delta_e\right) = \frac{1}{2}V_y\Delta_y + \eta V_y\left(\Delta_u - \Delta_y\right) \tag{7}$$

From the above formula, the energy correction factor γ can be obtained:

$$\gamma = \frac{1 + 2\eta\left(\mu_\Delta - 1\right)}{R_\mu^2} \tag{8}$$

In the formula

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} \tag{9}$$

$$R_\mu = \frac{V_e}{V_y} = \frac{\Delta_e}{\Delta_y} \tag{10}$$

In the formula, V_e and Δ_e respectively denote the base shear force and lateral displacement of elastic system; V_y, Δ_y and Δ_u respectively denote the base yield shear force, yield lateral displacement and ultimate displacement (the maximum permissible displacement) of elastic-plastic system; K_e denotes the rigidity of elastic system; R_μ denotes the ratio between base shear force (displacement) of elastic system and base yield shear force (yield displacement) of elastic-plastic system, which is called as the ductility reduction factor.

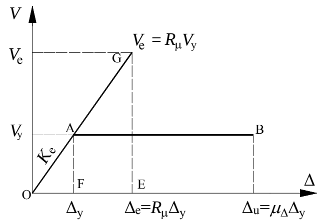


Figure 3. Force versus deformation

Ductility reduction factor R_μ mainly has connection with the ductility demand of the maximum displacement of the structure μ_Δ, natural vibration period and boundary conditions. Miranda et al. [21] has summarized relevant researches on relationship between R_μ and μ_Δ in the multi-degree-of-freedom system, and the researches show that the relationship between R_μ and μ_Δ proposed by Newmark et al. [22] comprehensively takes the influence of structural free vibration period on ductility reduction factor R_μ into consideration. Therefore, this chapter adopts the relational expression between R_μ and μ_Δ, which is shown in Table 1.

TABLE1. DUCTILITY REDUCTION FACTORS ACCORDING TO THE PERIOD RANGE

T Natural vibration period T	Ductility reduction factor R_μ
$0 \le T \le \frac{T_1}{10}$	$R_\mu = 1$
$\frac{T_1}{10} \le T < \frac{T_1}{4}$	$R_\mu = \sqrt{2\mu_\Delta - 1}\left(\frac{T_1}{4T}\right)^{2.513\log\left(\frac{1}{\sqrt{2\mu_\Delta - 1}}\right)}$
$\frac{T_1}{4} \le T < T_1'$	$R_\mu = \sqrt{2\mu_\Delta - 1}$
$T_1' \le T < T_1$	$R_\mu = \frac{T\mu_\Delta}{T_1}$
$T_1 \le T < 10.0\text{sec.}$	$R_\mu = \mu_\Delta$

Note: When the damping ratio is $\zeta = 5\%$, $T_1 = 0.57\text{sec.}$ $T_1' = T_1 \cdot \left(\sqrt{2\mu_\Delta - 1}/\mu_\Delta\right)\text{sec}$

Energy reduction factor η may be calculated according to the following formula.

$$\eta = A_1 / A_2 \tag{11}$$

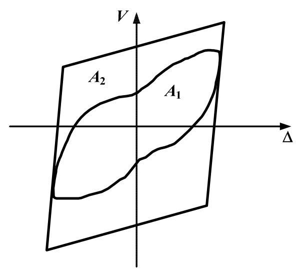


Figure 4. Elastic energy reduction factor diagram

In the formula, $A1$ and $A2$ are respectively area surrounded by outsourcing line of structural hysteretic curve and corresponding quadrilateral area (Fig.4). For the concrete structure, the reduction factor of hysteretic energy dissipation $\eta = 1/3$ [23] may be obtained.

B. Design Base Shear Force

Performance design method based on the optimum yield mechanism adopts the predetermined yield mechanism and expected targeted lateral displacement as the performance limit state (Fig.5a). According to the energy equal principle, the work required for structure to reach the targeted lateral displacement shall be equal to the energy required for equivalent elastic-plastic single-degree-of-freedom system to reach the same state (Fig.5b). Accordingly, the design base shear force under earthquake level prescribed shall be calculated.

In the formula (5), for the earthquake level prescribed (S_a which is known), the input earthquake energy can be written as:

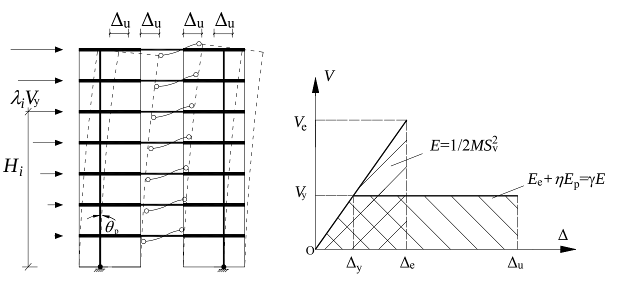
$$E = \left(\frac{1}{2}MS_v^2\right) = \frac{1}{2}M\left(\frac{T}{2\pi}S_a\right)^2 \tag{12}$$

In the formula, S_v is the spectrum speed; S_a is the spectrum accelerated speed; T is the basic natural vibration period; M is the total mass of system.

Elastic energy E_e can be determined by the following formula:

$$E_e = \frac{1}{2}M\left(\frac{T}{2\pi}\cdot\frac{V_y}{G}\cdot g\right)^2 \tag{13}$$

In the formula, G is the total representative value of gravity load of the structure; g is the gravity load acceleration; V_y is the base yield shear force.



(a) Yield mechanism (b) Energy of single-degree-of-freedom system – work balance

Figure 5. Yield mechanism-based plastic design

Plastic energy E_p is equal to energy dissipated by plastic hinge in the structure, which is shown in Fig.5(a). For the yield mechanism, the energy shall be:

$$E_p = V_y\left(\sum_{i=1}^{n}\lambda_i H_i\right)\theta_p \tag{14}$$

In the formula, λ_i is lateral load distribution factor of floor; H_i is the calculated altitude at the floor of the *ith* storey; θ_p is the plastic lateral drift angle.

Substitute formula (12), formula (13) and formula (14) into formula (5) and obtain $M = G/g$; then, obtain:

$$\frac{1}{2}\left(\frac{G}{g}\right)\cdot\left(\frac{T}{2\pi}\frac{V_y}{G}g\right)^2 + V_y\left(\sum_{i=1}^{n}\lambda_i H_i\right)\theta_p = \frac{1}{2}\frac{\gamma}{\eta}\left(\frac{G}{g}\right)\cdot\left(\frac{T}{2\pi}S_a\right)^2 \tag{15}$$

Or

$$\left(\frac{V_y}{G}\right)^2 + \left(\frac{8\pi^2\theta_p}{T^2 g}H^*\right)\frac{V_y}{G} - \frac{\gamma}{\eta}\left(\frac{S_a}{g}\right)^2 = 0 \tag{16}$$

Design base shear factor V_y/G is obtained by formula (15):

$$\frac{V_y}{G} = \frac{-\beta + \sqrt{\beta^2 + 4(\gamma/\eta)\left(S_a/g\right)^2}}{2} \tag{17}$$

In the formula, β is the dimensionless parameter, which is determined by the following formula:

$$\beta = \frac{8\pi^2\theta_p}{T^2 g}H^* \tag{18}$$

And $H^* = \sum_{i=1}^{n}\left(\lambda_i H_i\right)$.

C. Lateral Force Distribution

When the structure sustains rare earthquake action, the design lateral force distribution along the height of structure shall have capability of representing the practical interlaminar shear distribution f the structure. Define yield shear factor κ_i defined in storey of *i* as:

$$\kappa_i = \frac{V_{yi}}{\sum_{j=i}^{n}G_j} \tag{19}$$

Accordingly, the yield shear factor κ_1 in the 1st storey is:

$$\kappa_1 = \frac{V_{y1}}{\sum_{j=1}^{n} G_j} = \frac{V_y}{G} \quad (20)$$

In the formula, G_j and G are respectively the representative value of gravity load and total representative value of gravity load of the structure; V_{yi} and V_y are respectively the yield shear force and total yield shear force of the structure in the *i*th storey.

Define the yield shear distribution factor $\overline{\kappa_i}$ in the *i*th storey as the ratio between yield shear factor in the *i*th storey and that in the base storey (the 1st storey). Then:

$$\overline{\kappa_i} = \frac{\kappa_i}{\kappa_1} = \frac{V_{yi}}{\sum_{j=i}^{n} G_j} \Big/ \frac{V_y}{G} = \frac{V_{yi}}{V_y} \cdot \frac{G}{\sum_{j=i}^{n} G_j}$$

Yield shear force V_{yi} in the *i*th storey can be obtained from the above formula:

$$V_{yi} = \overline{\kappa_i} \frac{\sum_{j=i}^{n} G_j}{G} V_y = \overline{\kappa_i}\, \overline{G_i} V_y \quad (21)$$

In the formula:

$$\overline{G_i} = \sum_{j=i}^{n} G_j \Big/ G$$

Lateral force F_i in the *i*th storey can be denoted as:

$$F_i = V_{yi} - V_{y,i+1} = (\overline{\kappa_i}\,\overline{G_i} - \overline{\kappa_{i+1}}\,\overline{G_{i+1}})V_y = \lambda_i V_y \quad (22)$$

In the formula:

$$\lambda_i = \overline{\kappa_i}\,\overline{G_i} - \overline{\kappa_{i+1}}\,\overline{G_{i+1}} \; (i = n, \overline{\kappa_{i+1}}\,\overline{G_{i+1}} = 0)$$

In the formula, λ_i is the lateral force distribution factor of the floor.

Coupled shear wall is generally the shear-flexural structure, and the yield shear distribution factor $\overline{\kappa_i}$ of the storey can be determined according to the following formula [24].

$$\overline{\kappa_i} = \overline{\kappa_{si}} + 1.25\xi^4 \quad (23)$$

In the formula, $\overline{\kappa_{si}}$ is the yield shear distribution factor of floor with shear structure, and adopted according to the following provisions [24]:

When $\xi > 0.2$

$$\overline{\kappa_{si}} = 1 + 1.5927\xi - 11.8519\xi^2 + 42.5833\xi^3 - 59.4827\xi^4 + 30.1586\xi^5 \quad (24a)$$

When $\xi < 0.2$

$$\overline{\kappa_{si}} = 1 + 0.5\xi \quad (24b)$$

$$\xi = \frac{z}{H} = \frac{i-1}{n} \quad (25)$$

In the formula, H is the total calculated height of structure; *n* is the total number of storey of structure; *z* is the distance of lower section from fixed end of structure.

When the distribution of structural quality along the height is extremely inhomogeneous, ξ in the formula (23) and formula (24) shall be calculated according to the following formula:

$$\xi = \frac{i-1}{n} = 1 - \sum_{j=i}^{n} G_j \Big/ G \quad (26)$$

D. Section Design of Component

(1). Section design of coupling beam and lower end of wall column

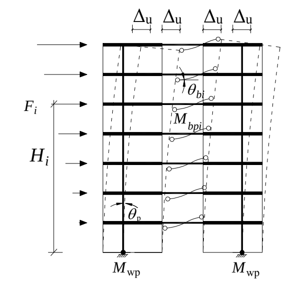


Figure 6. Target yield mechanism of coupled walls

Under the rare earthquake action and to avoid structural collapse and damages; dissipate input earthquake energy to an extreme and make the structure equipped with sufficient bearing capacity and ductility, it is necessary for structure to select a reasonable yield mechanism in the initial stage of design. When coupled shear wall adopts the targeted yield mechanism shown in Fig.6, the coupling beam becomes the designated yield component. Plastic moment required by coupling beam of each storey and lower section of base storey of wall column shall meet the following requirements (external work is equal to internal work):

$$\sum_{i=1}^{n} F_i H_i \theta_p = 2M_{wp}\theta_p + \sum_{i=1}^{n} 2M_{bpi}\,\theta_{bi} \quad (27)$$

In the formula, M_{bpi} is the plastic moment required by coupling beam in the *i*th storey; θ_{bi} is the plastic rotation angle of coupling beam and $\theta_{bi} = (l_w / l_b)\theta_p$; M_{wp} is the plastic rotation angle of lower section of wall column. Because the anti-symmetric deformation of coupling beam occurs, the work made by gravity load equally distributed is zero.

FEMA356 stipulates [25] that when the corresponding base shear force of the first vibration mode is less than 77% corresponding base shear under consideration of influences of high vibration, the influences of high vibration may not be taken into consideration. For structure of coupled shear wall, when meeting the above conditions, each coupling beam along structural height may be designed as the coupling beam with same bearing capacity. In such manner, the plastic moment in the formula (27) is $M_{bpi} = V_{bi} l_b / 2$, shear force coupling beam V_{bi} of which may be calculated according to the following formula:

$$V_{bi} = \frac{1}{n}\sum_{j=1}^{n} V_{bj} \tag{28}$$

In the formula, $\sum_{i=1}^{n} V_{bi}$ denotes the value of shear force undertaken by all coupling beams, which is determined according to formula (4); n is the total number of storey of the structure.

After plastic moment required by each storey of coupling beam is known, the plastic moment required by the lower section of base storey of wall column can be obtained by the formula (27). To guarantee that the lower section of base storey of coupled shear wall may finally enter the yield state under the earthquake action, the plastic moment of the lower section of wall column determined according to the formula (27) shall be multiplied by enlargement factor η_w :

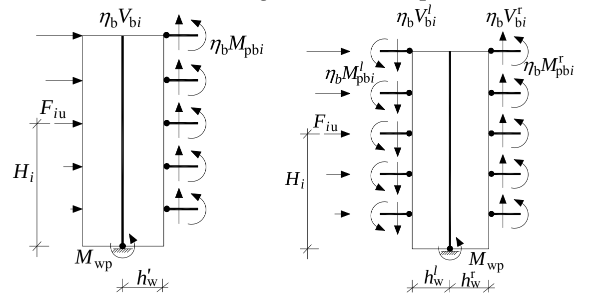
$$\eta_w = 1.2\frac{\sum_{i=1}^{n} V_{bpi}}{\sum_{i=1}^{n} V_{bi}} \tag{29}$$

In the formula, V_{bpi} denotes the corresponding shear value for end section of the ith coupling beam to reach the flexural capacity (the calculation is made according to actual planning steel area and characteristic value of material strength); V_{bi} denotes the design shear value of the ith coupling beam.

In addition, to guarantee that the section of coupling beam may not result in shear damages before reaching the flexural capacity, the existing specification [3] shall be followed to calculate the shear capacity of section of coupling beam and the requirement of strong shear capacity and weak bending capacity shall also be satisfied.

(2) Design of other sections of wall column

In the structural design of coupled shear wall, the system of coupled shear wall may be cut up along coupling beam, which is separated into independent vertical cantilever wall free body. Fig.7 shows the free body diagram of coupled shear wall at the time of targeted lateral displacement.



(a) Side wall column (b) Middle wall column

Figure 7. Free-body of coupled shear wall

To guarantee that the structure of coupled shear wall may be formed into expected yield mechanism, the design of wall column must have capacity of resisting the maximum anticipated load (including the gravity load undertaken by coupling beam and wall column); simultaneously, the strain hardening and material overstrength, potentiation of cast-in-place concrete floor to coupling beam and the reinforcement elastic-plastic model of coupling beam-end plastic hinge within a certain scope shall be taken into consideration. Plastic hinge moment adopted at the time of section design may be obtained by making required plastic moment M_{bpi} multiplied by appropriate overstrength factor η_b . By referring to relevant provisions on barrel and coupling beams between openings of shear wall of concrete specification [2], for common coupling beam, the overstrength factor η_b of seismic grades including Grade I, Grade II, Grade III and Grade IV may respectively be taken as 1.3, 1.2, 1.1 and 1.0. Coupling beam η_b with diagonal reinforcement is taken as 1.0.

Because the plastic bending moment M_{bpi} adopted in the formula (27) on plastic hinge moment ratio of coupling beam used at the time of section design is large, a certain lateral force is required for balance. Assume that the lateral force F_{iu} required for action on free body follows the distribution form provided by the formula (22), the quantity value can be obtained through balance conditions of the whole free body. In the structure of coupled shear wall, the sum of lateral force V_{ed} required for balance and acted on the free body of side wall column (Fig.7a) may be determined by the following formula:

$$V_{ed} = \frac{\eta_b \sum_{i=1}^{n} M_{bpi} + \eta_b \sum_{i=1}^{n} V_{bi} h'_w + \eta_w M_{wp}}{\sum_{i=1}^{n} \lambda_i H_i} \tag{30}$$

In the formula, h'_{w} is the distance of center of plastic hinge from centroidal axis of section of wall column.

For the free body of middle wall column (Fig.7b), the sum of lateral force V_{ed} may be calculated in follows:

$$V_{\mathrm{in}} = \frac{\eta_{\mathrm{b}}\sum_{i=1}^{n}\left(M^{\mathrm{r}}_{\mathrm{bp}i} + M^{l}_{\mathrm{bp}i}\right) + \eta_{\mathrm{b}}\sum_{i=1}^{n}\left(V^{\mathrm{r}}_{\mathrm{b}i}h^{\mathrm{r}}_{\mathrm{w}} + V^{l}_{\mathrm{b}i}h^{l}_{\mathrm{w}}\right) + \eta_{\mathrm{w}}M_{\mathrm{wp}}}{\sum_{i=1}^{n}\lambda_i H_i} \tag{31}$$

In the formula, $M^{l}_{\mathrm{bp}i}$ and $M^{\mathrm{r}}_{\mathrm{bp}i}$ respectively denote plastic moment required by left and right coupling beams of middle wall column; $V^{l}_{\mathrm{b}i}$ and $V^{\mathrm{r}}_{\mathrm{b}i}$ respectively denote the shear force required by left and right coupling beams of middle wall column; h^{l}_{w} and $h^{\mathrm{r}}_{\mathrm{w}}$ respectively denote the distance of center of left and right coupling beams from centroidal axis of section of wall column.

According to bending moment, shear force and lateral force F_{iu} acted on each storey of coupling beam end, the bending moment and shear force of each storey of section of wall column may be calculated; then, the bearing capacity of section of wall column may be calculated according to the existing specification [3].

IV. DESIGN STEPS

Steps of performance design method of structure of coupled shear wall based on control of yield mechanism are shown as follows:

(1) According to the design earthquake level, select the expected yield mechanism and targeted lateral drift angle θ_{u} consistent with anticipated performance objectives. That is to say that determination of targeted displacement depends on performance objective, which means the maximum degree of damage of structure expected at the time of occurrence of earthquake. Selection of targeted displacement may refer to relevant specifications and provisions in the report [3]. Assume that the force-displacement relationship of structure is the ideal elastic-plastic mode, and the yield lateral drift angle θ_{y} of structural shall also be estimated.

(2) Use preselected targeted lateral drift angle θ_{u} to subtract yield lateral drift angle θ_{y}, and then the plastic lateral displacement angle θ_{p} may be obtained.

(3) Estimate the structural basic natural vibration period *T* according to structural quality and rigidity characteristics.

(4) Adopt parameters determined in the step (1) and the step (2), and according to design spectrum acceleration magnitude S_{a}, the design base shear force V_{y} can be calculated by formula (17).

(5) Lateral force and distribution are determined by the formula (22), and according to the following formula, calculate the total capsizing moment at the structural bottom:

$$M_0 = \sum_{i=1}^{n} F_i H_i \tag{32}$$

(6) Select targeted coupling rate *CR*, and determine the total shear force of all coupling beams according to the formula (4).

(7) When the corresponding base shear force of the first vibration mode is less than 77% corresponding base shear under consideration of influences of high vibration, calculate the shear force of each coupling beam according to the formula (28), and then calculate plastic moment required by each coupling beam according to the following formula:

$$M_{\mathrm{bp}i} = V_{\mathrm{b}i} l_b / 2 \tag{33}$$

(8) Substitute plastic moment required by each storey of coupling beam into the formula (27) to determine plastic moment required by the lower section of base storey of wall column.

(9) Respectively calculate the lateral force for overall balance required by side and middle wall columns through the formula (30) and the formula (31), and make distribution along structural height according to the formula (22).

(10) According to bending moment, shear force and lateral force F_{iu} acted on each storey of coupling beam end, calculate the bending moment and shear force of each storey of coupling beam end.

(11) Calculate bearing capacity of sections of coupling beam and base storey of wall column according to the formula (34) and make structural lateral strength distribution meet design storey shear distribution; calculate the bearing capacity of other sections of wall column.

$$S_{\mathrm{GE}} + S_{\mathrm{Ek}}(I, \zeta) \le R_{\mathrm{k}} \tag{34}$$

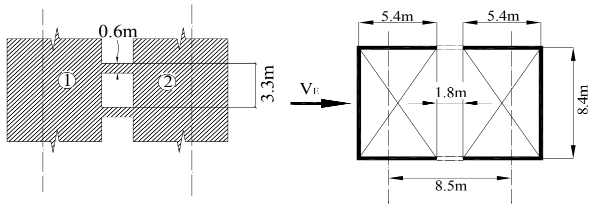
$$\gamma_{\mathrm{G}} S_{\mathrm{GE}} + \gamma_{\mathrm{Eh}} S_{\mathrm{Ehk}} \le R / \gamma_{\mathrm{RE}} \tag{35}$$

Meanings of signs in the formula are same with these in the literature [2].

V. CALCULATING EXAMPLE ANALYSIS

A. Project Overview

This project includes structure of 12-storey concrete core walls, and the specific dimension is shown in Fig.8. The height of base storey is 4.2m, and that of other storey is 3.3m. The thickness of wall column and coupling beam shall both be 0.2m, and the width of effective flange is 2.025m. Structure is located in area with Degree-8 design intensity and Class-II site, and the group of design earthquake is the second group. $T_g = 0.4s$ (middle earthquake), while $T_g = 0.45s$ (major earthquake). Representative values of total gravity load of each storey completely are 1380kN.



(a) Elevation drawing (b) Plane graph

Figure 8. Dimensions of the coupled wall structure

B. Design Process

Respectively calculate the base shear force of structure under the middle earthquake action and major earthquake action and see the step (1) to step (4). See Table 1 for main design parameters.

(1) According to the literature [2], design base shear force shall be determined based on two performance criteria: under Degree-8 middle earthquake action, the maximum lateral shift angle θ_u is 1/200; under Degree-8 rare earthquake action, the maximum lateral shift angle θ_u is 1/135. Yield lateral shift angle θ_y of structure estimated is 1/400.

(2) Calculate plastic lateral shift angle θ_p through targeted lateral shift angle θ_u and yield lateral angle θ_y.

(3) Estimate structural basic natural vibration period. Basic period of structure of coupled shear wall may be calculated according to the following formula:

$$T = 1.7\psi_T\sqrt{u_T} \tag{36}$$

In the formula, u_T denotes the hypothetical lateral displacement of peak of structure, which means the top lateral displacement obtained by each particle under the horizontal action of representative value of gravity load of each storey; ψ_T denotes period time deduction factor under consideration of influences of non-bearing wall, and the value of shear wall structure is from 0.9 to 1.0, while the value in this paper is 1.0.

Hypothetical lateral displacement u_T of peak of structure of coupled shear wall is calculated according to the following formula [1]:

$$u_T = \frac{V_0 H^3}{8E(I_1 + I_2)}\left[1 + \tau(\psi_a - 1) + 4\gamma_1^2\right] \tag{37}$$

In the formula, V_0 is the structural base shear force; γ_1 is the shear deformation factor of wall column. See the literature [1] for meanings of other signs.

From the above formula, it can be known that the basic period of calculating example is 0.807s.

TABLE 2. DESIGN PARAMETERS FOR THE COUPLED SHEAR WALL

Design parameters	Middle earthquake	Major earthquake
Targeted lateral displacement angle	1/200	1/135
Yield lateral displacement angle	1/400	1/400
$\theta_p = \theta_u - \theta_y$	0.25%	0.49%
α_{max}	0.45	0.90
S_a	0.239g	0.532g
$\mu_\Delta = \theta_u/\theta_y$	2.000	2.963
H^* /m	29.695	29.695
β	0.417	0.601
R_μ	2.000	2.963
γ	0.417	0.263
V_y/G	0.064378	0.105388
Design base shear force V_y /kN	1931.334	3161.648

(4) Calculate design base shear force V_y through the formula (16). According to the earthquake resistant code [2], the damping ratio ζ takes 0.05, and acceleration spectrum value S_a is determined by the following formula:

$$S_a = \left(\frac{T_g}{T}\right)^{0.9}\alpha_{max}g \quad \left(T_g \le T \le 5T_g\right) \tag{38}$$

In the formula, α_{max} is the maximum value of horizontal earthquake effect factor.

After the calculation, the design base shear force under major earthquake action is 1.637 times larger than that under middle earthquake action. Therefore, the design structure shall select and use the major earthquake for control. Each step in follows shall be calculated according to major earthquake action.

(5) Determine the lateral force and distribution through the formula (22), and calculate process table 2.

(6) Select the targeted coupling rate $CR = 0.6$, and through the calculation according to the formula (4), obtain that the total shear force of coupling beam is 3537.045kN.

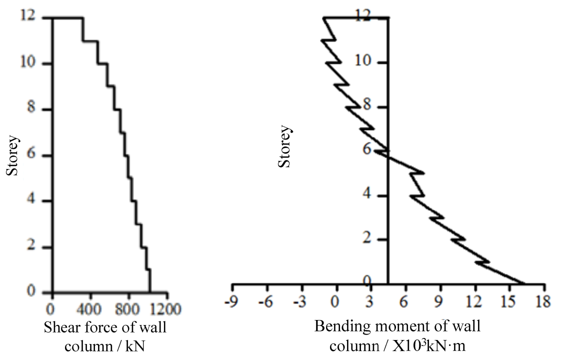
(7) Through the formula (28) and formula (33), respectively calculate shear force of each coupling beam and plastic moment required by each coupling beam; substitute plastic moment required by each storey of coupling beam into the formula (27) to determine that the plastic moment required by lower section of base storey of wall column is 2897.904kN·m. To guarantee that the lower section of base storey of coupled shear wall may finally enter the yield state under the earthquake action, the plastic moment of lower section of wall column determined according to the formula (27) shall be multiplied by enlargement factor $\eta_w = 1.2$, and then M_{wp} =9388.38 kN·m.

(8) According to the formula (30), calculate the sum V_{ed} of lateral force required for balance, and according to the formula (22), distribute the balance lateral force along structural height and see the last row of Table 2 for results.

See Fig.9 for bending moment calculated according to the above and shear force diagram.

TABLE 3. LATERAL FORCE DISTRIBUTION FOR THE COUPLED SHEAR WALL

Storey	$\bar{\kappa}_i$	λ_i	F_i /kN	F_iH_i /kN·m	F_{iu} /kN
12	3.731	0.237	982.996	39811.325	318.664
11	2.809	0.129	497.081	18491.402	161.142
10	2.253	0.096	300.834	10198.279	97.523
9	1.905	0.088	227.208	6952.560	73.655
8	1.666	0.081	186.779	5099.055	60.549
7	1.482	0.068	147.200	3532.810	47.719
6	1.331	0.053	112.657	2331.990	36.521
5	1.214	0.045	103.311	1797.614	33.491
4	1.136	0.050	134.762	1900.138	43.687
3	1.094	0.064	189.708	2048.844	61.499
2	1.052	0.054	165.919	1244.393	53.787
1	1.000	0.036	113.195	475.418	36.695



(a) Shear force diagram (b) Bending moment diagram

Figure 9. Diagram of shear force and bending moment of the coupled wall structure's wall pier

(9) According to the formula (34), calculate the bearing capacity for coupling beam and lower end of base storey of wall column, and according to the formula (35), calculate the bearing capacity for other sections of wall column. In the coupled shear wall, the grade of strength of concrete is C30; that of forced longitudinal steel is HRB400, and that of distribution steel and stirrup is HPB300. Strength of materials shall take standard value when calculating the bearing capacity of section of coupling beam and lower section of base storey of wall column, and it shall take design value when calculating the bearing capacity of other sections of wall column. See Table 3 for ratio *Ash/s* between the area of transverse distributed steel bar of section of base storey of wall column and the spacing and the longitudinal stirrup ratio ρ_s within the length of 800mm of restraint flange component for wall column of coupled shear wall. See Table 4 for stirrup ratio ρ_{sv} of coupling beam and the area A_s of longitudinal steel bar with unilateral tension.

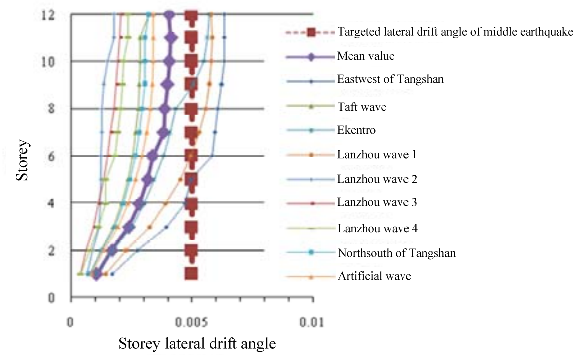
TABLE 4. REINFORCEMENT OF THE COUPLED WALL PIER' BOTTOM

Analysis method	Ash/s	ρ_s %
Method of this chapter	0.15	1.12
Elastic design of small earthquake	0.12	1.00

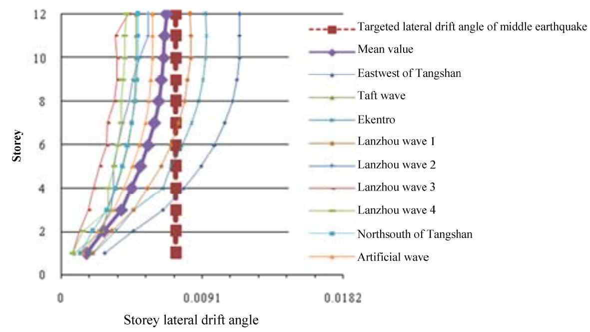
TABLE 5. REINFORCEMENT OF THE COUPLING BEAM

Analysis method	ρ_{sv} /%	A_s /mm2
Method of this chapter	0.326	985
Elastic design of small earthquake	0.284	605

C. *Finite Element Verification*



(a) Middle earthquake



(b) Major earthquake

Figure 10. Storey drifts for the coupled shear wall with target earthquake action under

Adopt SAP2000 procedure to make elastic-plastic time-history analysis. Wall and coupling beam shall respectively adopt multi-layer shell element and frame element models. Select 10 earthquake waves, including: Taft, EL Centro, Lanzhou wave 1, Lanzhou wave 2, Lanzhou wave 3, Lanzhou wave 4 and the east west of Tangshan Beijing

Hotel, the southwest of Tangshan, Taiwan Chi-Chi and artificial wave. Among them, the artificial wave takes response spectrum as the target spectrum, and is synthesized by using amplitude adjustment method.

See Fig.10 for envelope diagram of storey lateral shift angle obtained by analyzing 10 earthquake waves and comparison of targeted lateral shift angel. From the figure, the lateral shift angle obtained through time-history analysis and the targeted lateral shift angel are generally and relatively coincident.

D. Comparison with Elastic Design Results of Small Earthquake

According to the earthquake resistant code [2], the frequent intensive parameter calculation level, earthquake action and its effect as well as the corresponding effect of representative value of gravity load shall be combined; obtain section force design value of coupling beam and wall column; consider corresponding internal force adjustment; carry out the section design, and see Table 3 and Table 4 for design results. Through the comparison between elastic design of small earthquake and the design of method in this paper, the results show that:

(1) Method in this paper includes that the coupling beam selected shall firstly be yielded, and finally the wall column forms the yield mechanism of plastic hinge in the basic end face. Targeted lateral shift angle given is 1/135, and the coupling rate is 0.6. Calculated results show that the area of transverse steel bar in the section of base storey of wall column and the area of longitudinal steel bar in the section are respectively 1.25 times and 1.12 times larger than that of elastic section design of small earthquake and middle earthquake in the earthquake resistant code [2].

(2) At the time of design based on elasticity of small earthquake, the area of stirrup ratio of coupling beam and tensile longitudinal steel bar is respectively 87% and 61% of method in this paper.

(3) With the reduction of targeted lateral displacement, the reinforcement ratios of wall column and coupling beam are increased.

VI. CONCLUSION

(1) Based on the yield mechanism control and performance design idea of structure of coupled shear wall, this paper proposes the performance design method of structure of coupled shear wall based on the optimal yield mechanism.

(2) According to the method proposed, the structural design base shear force under yield mechanism and earthquake level given may directly be calculated, and the lateral force distribution of yield mechanism could be satisfied, which fully reflects the performance of coupled shear wall under the earthquake action provided.

(3) Use elastic-plastic time-history analysis method to make analysis, and compare with targeted lateral shift angle given, which verifies the reliability of recommended method.

(4) The area of transverse steel bar of section of base storey of wall column and the area of longitudinal steel bar of section obtained by calculating examples according to yield mechanism given and targeted lateral displacement are respectively 1.25 times and 1.12 times larger than that of elastic section design of small earthquake, and the stirrup ratio of coupling beam and the area of tensile longitudinal steel bar are respectively 1.15 times and 1.63 times larger than that of elastic section design of small earthquake.

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