Earthquakes and Structures, *Vol. 16, No. 1 (2019) 83-96*
DOI: https://doi.org/10.12989/eas.2019.16.1.083

Seismic performance and design method of PRC coupling beam-hybrid coupled shear wall system

Jianbo Tian*[1,2], Youchun Wang[1,2], Zheng Jian[1,2], Shen Li[1,2] and Yunhe Liu[1,2]

[1]School of Civil Engineering and Architecture, Xi'an University of Technology, Xi'an Beilin District, Jinhua Road No. 5, 710048, China
[2]State Key Laboratory Base of Eco-hydraulic Engineering in Arid Area, Xi'an University of Technology, Xi'an Beilin District, Jinhua Road No. 5, 710048, China

(Received June 1, 2018, Revised December 12, 2018, Accepted December 15, 2018)

Abstract. The seismic behavior of PRC coupling beam-hybrid coupled shear wall system is analyzed by using the finite element software ABAQUS. The stress distribution of steel plate, reinforcing bar in coupling beam, reinforcing bar in slab and concrete is investigated. Meanwhile, the plastic hinges developing law of this hybrid coupled shear wall system is also studied. Further, the effect of coupling ratio, section dimensions of coupling beam, aspect ratio of single shear wall, total height of structure and the role of slab on the seismic behavior of the new structural system. A fitting formula of plate characteristic values for PRC coupling beams based on different displacement requirements is proposed through the experimental date regression analysis of PRC coupling beams at home and abroad. The seismic behavior control method for PRC coupling beam-hybrid coupled shear wall system is proposed based on the continuous connection method and through controlling the coupling ratio, the roof displacement, story drift angle of hybrid coupled shear wall system, displacement ductility of coupling beam.

Keywords: PRC coupling beam-hybrid coupled shear wall system; coupling ratio; finite element analysis; seismic behavior; displacement-based seismic design method

1. Introduction

The PRC coupling beam-hybrid coupled shear wall system is a new type of structural system formed by replacing the concrete coupling beam in the traditional coupled shear wall with a plate-reinforced composite (PRC) coupling beam. The PRC coupling beam is a new type of coupling beam. By arranging steel plates in the concrete coupling beam, the steel plate and the reinforced concrete together resist the shearing force, and the reinforced concrete resists the bending moment. The good bearing capacity and plastic deformation ability of the steel plate not only improve the shear capacity of the coupling beam, but also prevent brittle fracture of the coupling beam, thereby improving the shear capacity and ductility of the coupling beam. Meanwhile, steel plate is a plane component, which can avoid the problems that the complicated connection structure of the common steel beam and the wall, and the amount of the stirrup can be reduced, and the construction is convenient. The PRC coupling beam is a new type of coupling beam that is worthy of research and promotion. It has the advantages of both reinforced concrete coupling beams and steel coupling beams. It is a form of coupling beam with better comprehensive performance.

Three proposed steel plate-reinforced high toughness-concrete (PRHTC) coupling beams with different span-to-depth ratios (l/h=1.0, 1.5, and 2.0) and various steel plate reinforcement ratios were tested by (Hou *et al.* 2018 and 2019), all three PRHTC coupling beams behaved in a ductile manner with good hysteretic behavior and large energy-dissipating capacity. Both the embedded steel plates and the high-toughness concrete contributed greatly to the high performance of the PRHTC coupling beams. Two approximately half-scale four-story coupled shear wall specimens were tested under both gravity and lateral displacement reversals by Cheng *et al*. (2014), research results indicate that a ductile coupling beam design does not guarantee a ductile behavior of a coupled shear wall system, RC shear walls should be proportioned for axial and shear based on the provided coupling beam capacities. (Harries *et al*. 1998, 2000) conducted four steel coupling beam and shear wall joint experiments. Three of the experiment pieces ensured that the shear yield of the steel beam precedes the bending yielding, and the structural measures of the steel coupling beam embedded area are strengthened to meet the design requirements. And through the four full-size coupled wall structure specimens by Harries and EERI (2001), which gives the upper limit of the coupling ratios of 50%, 55%, 60% and 65%, respectively. A series of nonlinear time history analyses on various representative hybrid coupled walls are carried out to examine the adequacy of the design methodology by Hung and Lu (2015), while the proposed design method is shown to be able to facilitate the desired yielding mechanism in hybrid coupled walls, it is also able to reduce the adverse effects caused by the current design guidelines on the structural design and performance. The publications (Shahrooz *et al*. 1993, Gong and Shahrooz 2001) designed three specimens

∗Corresponding author, Lecturer
E-mail: tianjianbo@xaut.edu.cn

ISSN: 2092-7614 (Print), 2092-7622 (Online)

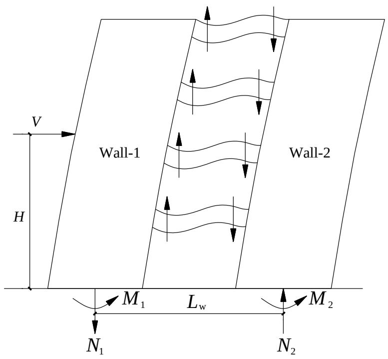


Fig. 1 Definition of coupling ratio

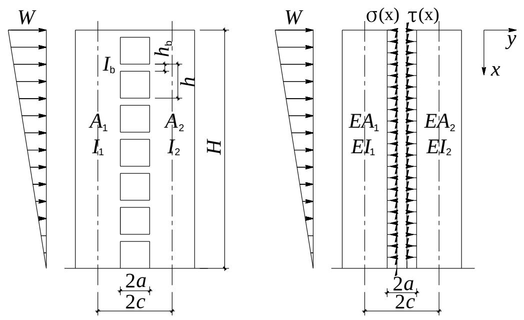


Fig. 2 Calculation diagram of coupled shear wall

of joints (1/2 reduced scale), mainly studied the shear transfer process between steel coupling beam and reinforced concrete wall. Studies have shown that the vast majority of the total energy dissipation of the structure is dissipated through the steel beam, and the wall contributes little to the overall energy dissipation.

In summary, there is still no systematic research on the new structural system of PRC coupling beam-hybrid coupled shear wall system. The damage evolution process, failure mechanism, bearing capacity, deformation performance and design method of such hybrid coupled shear wall system are necessary to study, and also meet the development direction of high-rise building structure.

2. Design parameters of PRC coupling beam-hybrid shear wall system analysis model

2.1 Calculation formula of coupling ratio CR

The coupling ratio of the hybrid coupled shear wall system is defined as the ratio of the total overturning moment resisted by the coupling action to the total overturning moment, the coupling ratio is represented by *CR*

$$CR = \frac{Nl_w}{\sum M_w + Nl_w} = \frac{Nl_w}{M_0} \tag{1}$$

In the formula, M_0 is the total overturning moment of the coupled shear wall. The $\sum M_w$ is the sum of the overturning moments in individual wall piers; N is the resultant force of the shear force within the beam end, and $N_1=N_2=N$ when the structure is symmetrical coupled shear wall system; l_w is the distance between centroids of wall piers.

The continuous link method is an approximate method, which is to assume that the coupling beam on each floor is supposed to be uniformly distributed along the floor height, and to establish the differential equation to calculate the internal force and displacement of the shear wall according to the principle of force method. Fig. 2 is the calculation diagram of the coupled shear wall under the horizontal load of inverted triangles.

The expression of the wall axial force by means of continuous connection method is as follows

$$N = \int_0^H \tau(x)\mathrm{d}x \tag{2}$$

Under the action of horizontal distribution of inverted triangle, the solution of differential equation is as follows

$$\Phi(\xi) = 1-(1-\xi)^2 + \left[\frac{2\mathrm{sh}\alpha}{\alpha} - 1 + \frac{2}{\alpha^2}\right]\frac{\mathrm{ch}\alpha\xi}{\mathrm{ch}\alpha} - \frac{2}{\alpha}\mathrm{sh}\alpha\xi - \frac{2}{\alpha^2} \tag{3}$$

$$\alpha^2 = \alpha_1^2 + \frac{3H^2D}{hcS} \tag{4}$$

$$\alpha_1^2 = \frac{6H^2}{h\sum I_i}D \tag{5}$$

$$D = \frac{\tilde{I}_b c^2}{a^3}, \quad S = \frac{2cA_1A_2}{A_1 + A_2} \tag{6}$$

$$T = \frac{\alpha_1^2}{\alpha^2} \tag{7}$$

In the formula, $2a$ is a coupling beam clear span, the $a=a_0+h_b/4$: h_b is taken as the section height of the coupling beam, the a_0 is 1/2 clear span, h is the layer height, $\tilde{I}_b$ is the reduced inertia moment of the coupling beam, when the G=0.4E (E and G are respectively the elastic modulus and the shear modulus of the concrete), can be calculated according to the following formula

$$\tilde{I}_b = \frac{I_b}{1 + \dfrac{7.5\mu I_b}{A_b a^2}} \tag{8}$$

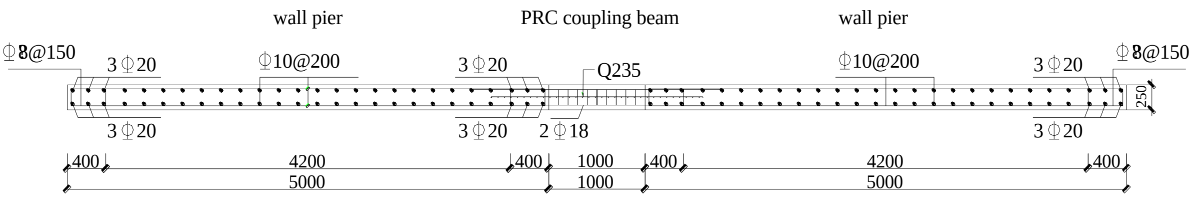
In the formula, A_b and I_b are respectively the section area and the inertia moment of the coupling beam, μ is non-uniform factor of shear stress of section, when the section is rectangular section, μ=1.2.

The coupling rate of the coupled wall is obtained by substituting the Eq. (2) into the Eq. (1) and the inverted triangular horizontal distribution of the integral

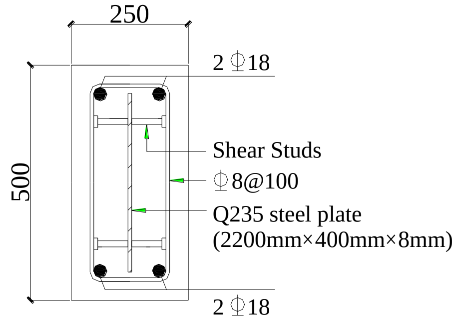
$$CR = \frac{3T}{\alpha^2}\left[\frac{\alpha^2}{3} - \mathrm{ch}\alpha + (\mathrm{sh}\alpha - \frac{\alpha}{2} + \frac{1}{\alpha})\mathrm{th}\alpha\right] \tag{9}$$

2.2 BS basic model design parameters

Considering that PRC coupling beam-hybrid shear wall system is usually used in high-rise buildings, a 12-storey



(a) Dimensions and reinforcement of wall and coupling beams



(b) Sectional dimensions of coupling beams and detail of reinforcement

Fig. 3 BS specimen model size and reinforcement drawing (unit: mm)

Table 1 CR-S series specimen design parameters

Series	Specimen number	Section size of coupling beam/mm	Single side longitudinal reinforcement of coupling beam	Steel plate Section Height h_p/mm	Thickness of steel plate section t_p/mm	Length of steel plate l_p/mm	Anchorage length of steel plate l_a/mm
CR-S	CR-S-30	220×250	2B12	170	8	1540	270
	CR-S-40	280×250	2B14	220	8	1680	340
	CR-S-50	400×250	2B16	320	8	1960	480
	CR-S-55	500×250	2B18	400	8	2200	600
	CR-S-60	640×250	2B20	520	8	2540	770
	CR-S-65	1000×250	2B25	810	8	3400	1200

Note: The CR-S-55 is the same size as the BS specimen.

reinforced concrete shear wall structure is used to study the symmetrical coupled shear wall. The structure layer is 2.8 m, total height 33.6 m, the wall piers and the coupling beam thickness are 0.25 m, the concrete strength grade is C40, the reinforcement all adopt the HRB335, the coupling beam embedded steel plate uses the Q235. The coupling rate is 55%, named BS specimen, the size and reinforcement of BS specimen finite element model are shown in Fig. 3, the axial force of BS specimen is applied to the top floor according to the design axial compression ratio of 0.2.

2.3 Selection of model design parameters

This chapter mainly studies the influence of the section size of the coupling beam, the aspect ratio of one side wall, the total floor height and the role of the floor to the bearing capacity, internal force distribution, deformation performance, and plastic hinge development law of the structure system. The influence of the distribution of internal force and the development of plastic hinge, the coupling rate of the coupling wall can be changed at the same time because of the section size of the beam, the aspect ratio of one side wall and the total floor height, so the coupling rate is taken as the supplementary factor, and each factor is set up 2-6 levels.

2.3.1 Influence of section size of coupling beam (CR-S series)

The CR-S series mainly studies the influence of the section size of the PRC coupling beam on the seismic behavior of PRC coupling beam-hybrid shear wall system, the shear wall section size and the total floor height h are unchanged, the essence is to change the coupling rate by changing the integral working coefficient α of the coupled shear wall. CR-S series specimen model design parameters as shown in Table 1, CR-S-30, CR-S-40, CR-S-50, CR-S-55, CR-S-60, CR-S-65 respectively represent the coupling rate of 30%, 40%, 50%, 55%, 60%, 65% of the specimen.

2.3.2 Single wall piers aspect ratio influence (CR-W series)

The CR-W series mainly studies the influence of the aspect ratio of one side wall to the seismic behavior of PRC coupling beam-hybrid shear wall system, the section size and the total floor height H of the PRC coupling beam are unchanged, and the objective is to change the coupling rate by changing the integral working coefficient α and the pier strength coefficient ζ of the PRC coupling beam-hybrid coupled shear wall system. CR-W series specimen model design parameters as shown in Table 2, CR-W-45, CR-W-55, CR-W-65 respectively represent the coupling rate of

Table 2 CR-W series specimen design parameters

Serial numbering	Specimen number	Dimensions of single wall piers/mm	Aspect ratio of wall piers
CR-W	CR-W-45	9000×250	3.73
	CR-W-55	5000×250	6.72
	CR-S-65	3000×250	11.2

Note: The CR-W-55 is the same size as the BS specimen.

Table 3 CR-H series specimen design parameters

Serial numbering	Specimen number	Number of floors	Coupling ratio/%	Aspect ratio of wall
CR-H	CR-H-12	12	55	6.72
	CR-H-15	15	60	8.4
	CR-H-20	20	65	11.2

Note: The CR-H-12 is the same size as the BS speciment.

Table 4 FS series specimen design parameters

Serial numbering	Specimen number	Floor width /mm	Floor thickness /mm	Horizontal and vertical distribution reinforcements of floor slab
FS	FS-Y	2000	180	B10@200
	FS-W	/	/	/

45%, 55%, 65% of the specimen.

2.3.3 Total floor Height Impact (CR-H series)

The CR-H series mainly studies the influence of the number of structural floors on the seismic behavior of PRC coupling beam-hybrid shear wall system, the section size of PRC coupling beam and the section dimension of shear wall are unchanged, in essence, the purpose of changing the coupling ratio is by changing the aspect ratio of the PRC coupling beam-hybrid coupled shear wall system. This series selects 12, 15 and 20-storey three floor heights, CR-H series specimen model design parameters and corresponding coupling ratios as shown in Table 3.

2.3.4 Consider the role of the floor (FS series)

In practical engineering, most of the coupling beams are poured together with the floor slab, the floor has a certain binding effect on the edge of the coupling beam, and at present it has not been found at home and abroad that the effect on the seismic performance of PRC coupling beam-hybrid shear wall system is reported. FS series the main take into account the effect of floor slab on the seismic behavior of PRC coupling beam-hybrid shear wall system, the floor size and reinforcement as shown in Table 4.

3. The establishment of Abaqus finite element model

3.1 The establishment of finite element model

The concrete compression damage plastic model provided by ABAQUS software includes rising straight section, rising curve section and descending curve section. When defining the elastic segment, the elastic limit point ($\varepsilon_{c,e0}$, $\sigma_{c,e0}$) must be determined first. It is recommended to take σ_c,e_0=1/3f_c, and calculate the initial tangential elastic modulus of the concrete

$$E_0 = \sigma_{c,e0} / \varepsilon_{c,e0} \tag{10}$$

By comparing the compressive stress-strain relationship of several widely used concretes, the publication (Saenz 1964) is used in the curve section

$$\sigma = \frac{E_0 \varepsilon}{1 + \left(\beta + \frac{E_0}{E_s} - 2\right)\left(\frac{\varepsilon}{\varepsilon_0}\right) + (1 - 2\beta)\left(\frac{\varepsilon}{\varepsilon_0}\right)^2 + \beta\left(\frac{\varepsilon}{\varepsilon_0}\right)^3} \tag{11}$$

Where ε_0 is the strain corresponding to the peak stress σ_0; ε_u is the strain corresponding to the ultimate stress σ_u; E_0 is the origin tangent modulus; E_s is the maximum stress point secant modulus, E_s=σ_0/ε_0; β is the coefficient, calculated as follows

$$\beta = \frac{E_0 / E_s(\sigma_0 / \sigma_u - 1)}{(\varepsilon_u / \varepsilon_0 - 1)^2} - \frac{\varepsilon_0}{\varepsilon_u} \tag{12}$$

The evolution equation of the compressive damage of concrete is

$$D = 1 - \sqrt{\sigma / (E_0 \varepsilon)} = 1 - 1 \Big/ \sqrt{1 + \left(\alpha + \frac{E_0}{E_s} - 2\right)\left(\frac{\varepsilon}{\varepsilon_0}\right) + (1 - 2\alpha)\left(\frac{\varepsilon}{\varepsilon_0}\right)^2 + \alpha\left(\frac{\varepsilon}{\varepsilon_0}\right)^3} \tag{13}$$

Where D is the damage variable; σ is the stress; ε is the strain.

When the concrete tensile strain exceeds the tensile elastic limit strain ε_{t0}, it will enter the tension softening section. The concrete tension softening section curve is determined by the relationship between the concrete tensile stress σ_t and the cracking strain ε_{ck} (Seongwoo *et al.* 2014). The cracking strain ε_{ck} is calculated as follows

$$\varepsilon_{ck} = \varepsilon_t - \sigma_t / E_0 \tag{14}$$

Where ε_t and σ_t are the strains and stresses at any point on the softening section curve of the concrete tensile stress-strain relationship curve, respectively.

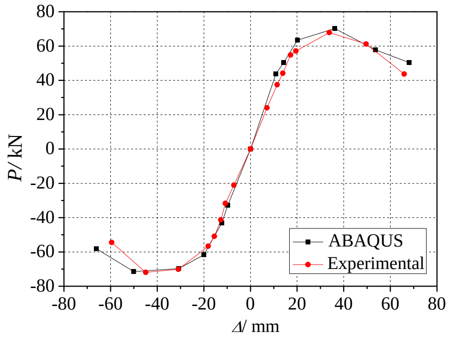
The stress-strain relationship of the concrete during the softening stage is generally in the form of a straight line, and the softening modulus is related to the concrete fracture energy G_f and the concrete element characteristic size l_c. The magnitude of the fracture energy can be calculated by the "stress-crack width" curve of the concrete when it is pulled and the area enclosed by the transverse axis (Wang *et al.* 2017). The cracking strain is equal to the ratio of the crack width ω to the characteristic length l_c of the concrete element, so the concrete is softened by the tensile modulus. The amount can be calculated as follows

$$E_{ts} = f_t / \varepsilon_{tu} = 0.5 f_t^2 l_c / G_f \tag{15}$$

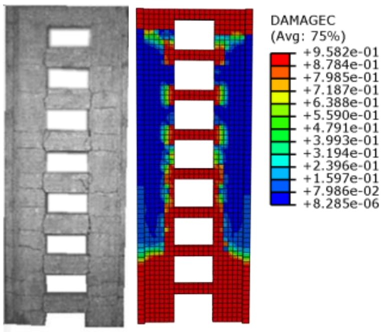
In the formula, ε_{tu}=ω_u/l_c=2G_f/($f_t l_c$); The fracture energy G_f is calculated according to the recommendations of the European specification (CEP-FIP Model Code 90)

$$G_f = \alpha \left(\frac{f_c'}{10}\right)^{0.7} \times 10^{-3} \text{ (N/mm)} \tag{16}$$

Among them, α=1.25d_{max}+10, d_{max} is the particle size of the coarse aggregate, f_{ck} is the compressive strength of



(a) Comparison of skeleton curves



(b) Comparison of results

Fig. 4 Comparison of experiment and simulation

the concrete, and the peak tensile stress of the concrete σ_{t0} is calculated by the calculation formula of the tensile strength of the concrete

$$\sigma_{t0} = 0.26 \times (1.5 f_{ck})^{2/3} \tag{17}$$

The nonlinear behavior of the steel plate and the reinforcement is a two-line strengthening model. The initial elastic modulus of the reinforcement is E_0, and the elastic modulus of the strengthening segment is $0.01E_0$.

When neglecting the bond-slip phenomenon between the steel plate and the concrete, the accuracy of the calculation result has little effect (Su *et al.* 2008), and the calculation efficiency is higher. Therefore, the contact relationship between the steel plate and the concrete, the reinforcement and the concrete are defined by the embedded method.

Finite element mesh generation using the structure of grid division technology, after calculation, considering the calculation of precision requirements and computational efficiency, the shear wall of some concrete and reinforced mesh density of 500 mm, PRC coupling beam mesh density of 100 mm.

3.2 Model validation

Because of the lack of the experimental research on the PRC coupling beam-hybrid coupled shear wall system at home and abroad, in order to verify the rationality and reliability of the finite element model, the paper simulates 1/7 scale 8-storey reinforced concrete symmetrical coupled shear wall specimen in the literature (Huang *et al.* 2005) by using Abaqus software, and the specimen number is SW. The pseudo-static test was used to study the seismic performance, and the horizontal low cyclic loading was applied to the top of the specimen.

The SW specimen was simulated by Abaqus, and the load-displacement skeleton curves of the specimen was simulated and tested in Fig. 4.

From Fig. 4(a), the calculated curves of specimen is in good agreement with the measured ones, and the peak loads and their corresponding displacements and ultimate loads are similar to those of the test results, and the skeleton curves are basically the same. Fig. 4(b) shows a comparison of the damage patterns between the simulation results of the SW specimen and the experimental results. During the finite element simulation loading process, the concrete damage of the wall under compression was observed to reach the maximum value (DAMAGEC indicates that the concrete damage under compression) It can be seen that the finite element analysis results are consistent with the regularity of the test results, and the deviation is within acceptable range, therefore, the model is effective.

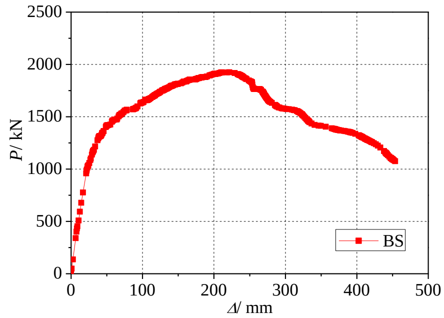


Fig. 5 BS basic model specimen load-top displacement curve

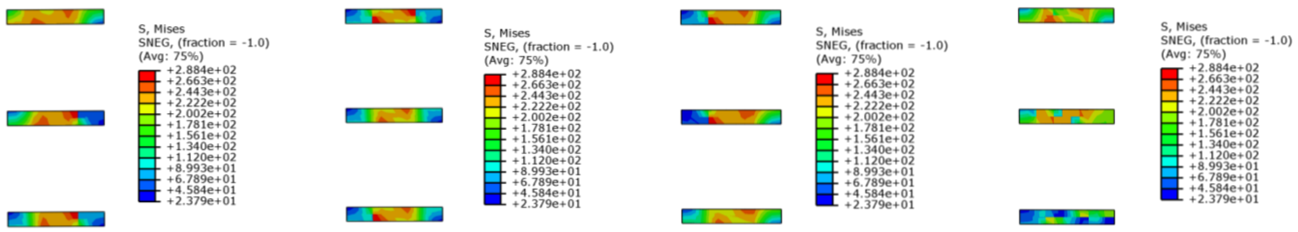
Table 5 BS basic model specimen bearing capacity and deformation capacity at each stage

Specimen number	Yield point		Peak point			Failure point		
	P_y/ kN	Δ_y/ mm	P_m/ kN	Δ_m/ mm	Displacement ductility μ_m	P_u/ kN	Δ_u/ mm	Displacement ductility μ_u
BS	1574.82	87.74	1924.32	221.55	2.53	1635.67	280.27	3.19

4. Analysis of the mechanical behavior of the basic BS model of PRC coupling beam-hybrid coupled shear wall system

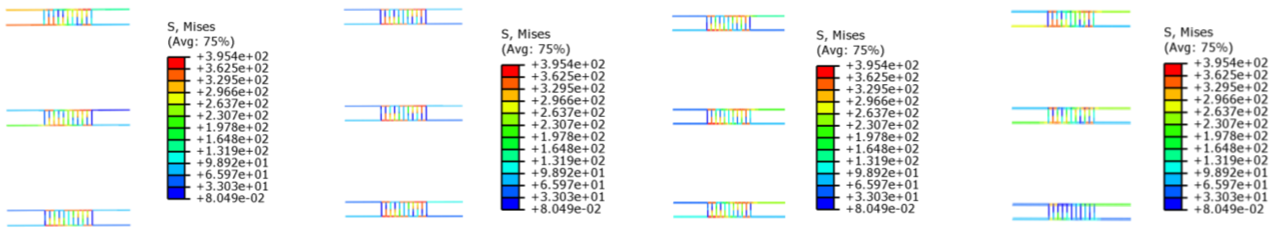
4.1 Bearing capacity and displacement ductility

Fig. 5 is the P-Δ curve of the BS basic model specimen of PRC coupling beam-hybrid shear wall system under monotonic loading, p is the total shear force at the bottom of the structure, and Δ is the top displacement of the structure. Table 5 gives the ductility coefficient of displacement and displacement of the BS basic model specimen at yield point, peak point and failure point. It is shown from Table 5 that the displacement ductility coefficients of the peak point and the failure point of BS basic model specimens are 2.53 and 3.19 respectively, and the final ductility coefficient is bigger than 3, which shows that BS hybrid coupled shear wall structure has undergone a



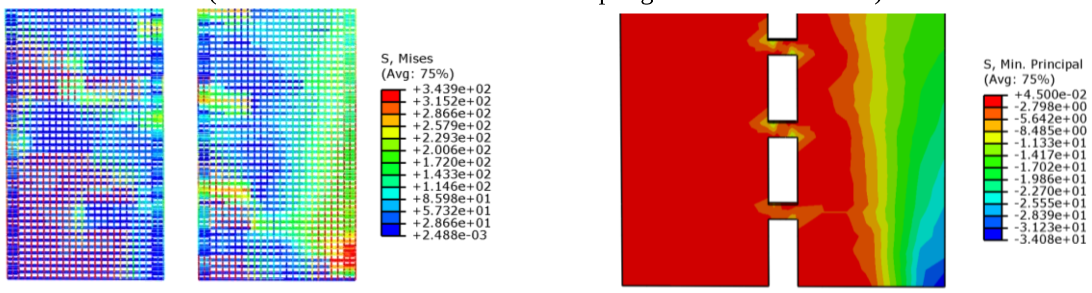
(a) 10-12-storey (b) 7-9-storey (c) 4-6-storey (d) 1-3-storey

(Von Mises stress distribution of coupling beam steel plate)



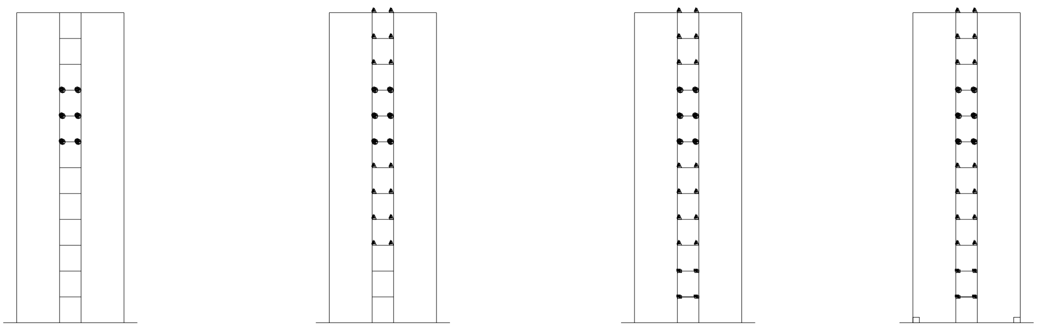
(e) 10-12-storey (f) 7-9-storey (g) 4-6-storey (h) 1-3-storey

(Von Mises stress distribution of coupling beam reinforcement)



(i) Von Mises stress distribution of the bottom reinforced (j) Compressive stress distribution of concrete at the bottom of wall

Fig. 6 Stress diagram of each specimen when the top displacement is 225.75 mm



(a) Displacement 23 mm (b) Displacement 44 mm (c) Displacement 114 mm (d) Displacement 158 mm

●-First batch plastic hinge ▲-second batch plastic hinge

■-third batch plastic hinge □-fourth batch plastic hinge

Fig. 7 Development sequence of plastic hinge

long process from the yield stage to the failure stage.

4.2 Stress analysis

The stress development law of the specimen reflects the damage form of the structure from the microcosmic, and the stress development of PRC coupling beam-hybrid coupled shear wall system BS basic model specimen in characteristic stage is shown in Fig. 6. The embedded steel plate section of PRC coupling beam is small, for the convenience of observation, the stress distribution of the embedded steel plate and the reinforcement of each floor is given in sections.

When the top displacement of the structure reaches 225.75 mm, the stress of the reinforced Von Mises in the left wall piers is increased rapidly, the stress of the reinforcement exceeds the yield stress 335 MPa, and the bottom of the left wall piers is yielded. The maximum compressive stress of concrete in the bottom compression zone of the wall is 34.08 MPa, exceeding the compressive strength of concrete, and the maximum compressive stress of concrete is distributed in the compressive region of the right wall, at this time the peak load point of the structure load-displacement curve. BS basic model structure reaches the peak load point due to the successive yielding of the PRC coupling beam, the tensile failure of the tensile wall and the crushed concrete in the compression area, which accords with the design requirement of “strong shear and weak bending”.

4.2 Development of plastic hinge

Fig. 7 shows the development sketch of the plastic hinge of BS basic model specimen. As can be seen from Fig. 7, when the top displacement of the structure reaches 23 mm, the largest part of the stress is in the 7th to 9th layer of PRC coupling beam, and it is also the first area to form the plastic hinge. With the increase of the load of the structure, when the structure top displacement reaches 44mm, the coupling beam of the 3-12 layer forms plastic hinge respectively, when the structure top displacement reaches 114 mm, the PRC coupling beam of 1-2 layer also forms the plastic hinge, the structure has entered the yielding state, and with the further increase of load, the longitudinal reinforcements of the bottom edge of the wall piers yield , the wall energy dissipation through the rotational capacity of the plastic hinge of the bottom wall piers, until the ultimate damage, all the PRC coupling beams yield, the reinforcement at bottom of the wall to reach the ultimate stress, compressive area of concrete crushing, load reached the ultimate bearing capacity of 85%, the structure to achieve damage.

5. Analysis of influence factors on mechanical properties of PRC coupling beam-hybrid coupled shear wall system

5.1 Influence of section size of coupling beam

Fig. 8 reflects the change of the coupling rate caused by the change of the section size of the PRC coupling beam to the influence of the load-displacement skeleton curve of the structure, for the CR-S series, with the increase of the coupling rate of the PRC coupling beam-hybrid coupled shear wall system, the initial stiffness of the specimen increases, which is mainly due to the increase of the coupling rate, which reduces the bottom bending moment of the wall, delays the crack speed of the wall piers, and improves the stiffness of the specimen.

As can be seen from Fig. 8, for the CR-S series, with the increase of coupling rate, the bearing capacity and ultimate bearing capacity of the structure yield increase gradually, compared with the ultimate bearing capacity of CR-S-30 specimen, because of the increase of coupling rate, the ratio of overturning moment of PRC coupling beam resisting earthquake was improved. When the coupling ratio is greater than 60%, with the increase of the coupling rate, the ultimate bearing capacity of the structure decreases.

For the specimens with coupling rate of 30% and 55%, the displacement ductility coefficients were 3.86 and 3.19

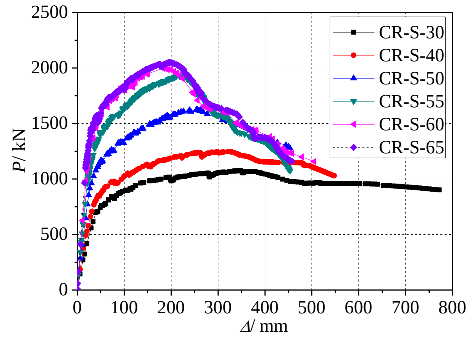


Fig. 8 The influence of the PRC coupling beam section size on the load-vertex displacement curve

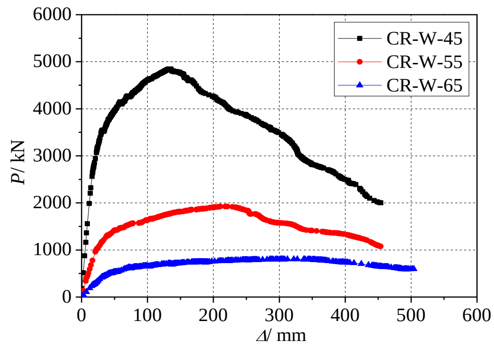


Fig. 9 The influence of the aspect ratio of single wall piers on the load-vertex displacement curve

according to the energy equivalent area method, and the displacement ductility coefficient of the structure failure was decreased and then increased and then decreased with the increase of coupling rate.

The results of finite element analysis of CR-S series of specimens show that the increase of the stiffness degree of PRC coupling beam has the overall stiffness and the bearing capacity has been greatly improved, but due to the coupling effect, when the coupling rate is greater than 60%, the yield mechanism becomes the PRC coupling beam does not yield, and the coupled shear wall only forms plastic hinge on the bottom of the wall piers, the ductility of the structure is reduced and the structure is destroyed earlier. The PRC coupling beam section size is too small, resulting in a small structure coupling rate, not conducive to the improvement of shear wall stiffness, will cause the coupling beam in the use of premature yield, not conducive to normal use, therefore, the coupling rate should be controlled in a suitable range.

5.2 Influence of aspect ratio of single wall piers

Fig. 9 reflects the change of coupling rate caused by the change of the aspect ratio of one-sided wall piers to the influence law of the load-displacement skeleton curve of the structure.

As can be seen from Fig. 9, for the CR-W series, with the increase of the coupling rate of the PRC coupling beam-hybrid coupled shear wall system, the initial stiffness of the specimen is gradually reduced, which is mainly due to the increase of the strength coefficient of the ζ, the increasing

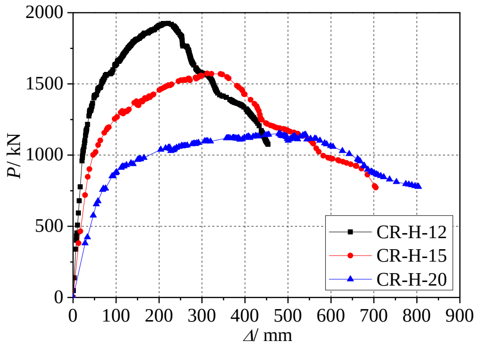


Fig. 10 The influence of the total floor height on the structure load-vertex displacement curve

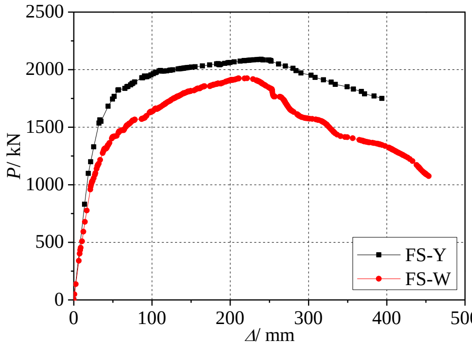


Fig. 11 The influence of slab action on the structure load-vertex displacement curve

of the shear wall's section weakening degree, the decrease of the shear wall stiffness and the lower lateral load resistance of the wall, and with the decrease of the width of the wall piers, the bearing capacity and ultimate bearing capacity of the structure are reduced gradually, the ultimate bearing capacity of CR-W-55 and CR-W-65 specimens is reduced by 60.29% and 83.36%, compared with the ultimate bearing capacity of the CR-W-45 specimen. It also shows that the more the wall piers section is weakened, the lower the ultimate bearing capacity of the specimen is larger.

5.3 Influence of total floor height

Fig. 10 reflects the change of the coupling rate caused by the change of the total floor height, and the influence law of the load-displacement skeleton curve of the structure.

As you can see from Fig. 10, as the number of floors increases, the initial stiffness of the specimen decreases gradually, and the ultimate bearing capacity of the structure decreases gradually, because the increase of the number of floors, the overturning moment of the bottom of the wall also increase under the same load, which increases the aspect ratio of the wall piers and the coupling rate of the structure.

For the CR-H series, with the increase of the number of floors, the aspect ratio of the wall is increased, the bearing capacity and ultimate bearing capacity of the structure are reduced gradually, and the ultimate bearing capacity of CR-H-15 and CR-H-20specimens is reduced by 18.24% and 40.16% respectively compared with the ultimate bearing capacity of CR-H-12 specimens.

The overall aspect ratio of the wall piers increases after the increase of the total floor altitude, the coupling rate of the structure is improved, and the increase of coupling rate increases the resisting overturning ability of the structure, but at the cost of the ductility of the structure, the displacement ductility coefficient of the structure decreases gradually, the displacement ductility of the specimen is the most CR-H-12, that is, the specimen with a coupling ratio of 55%. Compared with the displacement ductility coefficient of the specimen with CR-H-12 structure failure, the CR-H-20 displacement ductility coefficient of the specimen with coupling ratio of 65% is decreased by 13.17%.

5.4 Consider the role of the floor

Fig. 11 reflects the effect of the slab action on the load-displacement skeleton curve of the structure.

As can be seen from Fig. 11, the initial stiffness of the PRC coupling beam-hybrid shear wall system FS-Y considering the role of the slab is significantly higher than that of the PRC coupling beam-hybrid shear wall system, which does not take into account the role of the slab, it is indicated that the longitudinal reinforcements in the slab are involved in the flexural action of PRC coupling beam, thus improving the PRC coupling beam-hybrid shear wall resistance to lateral stiffness.

The FS-Y specimen of PRC coupling beam-hybrid shear wall system considering the effect of floor slab, the bearing capacity and ultimate bearing capacity of the structure yield are increased, as far as the ultimate bearing capacity is concerned, the FS-Y specimen considering the effect of floor slab is higher than that of the FS-W specimen 8.56%.

The displacement ductility coefficient of PRC coupling beam-hybrid coupled shear wall system FS-Y considering the effect of floor slab is significantly higher than that of PRC coupling beam-hybrid coupled shear wall system with no consideration of floor slab, and the displacement ductility coefficient of FS-Y specimen is 73.58% higher than that of FS-W specimen.

6. A fitting formula of plate characteristic values for PRC coupling beams based on the demand of displacement angle

In this paper, the test data of PRC coupling beam under 37 uniaxial or horizontal cyclic loadings at home and abroad are collected, in this section, 8 PRC coupling beam specimens with flexural-shear failure and flexural failure are added, and 11 specimens with no statistical limit displacement angle are excluded, this section gives 34 test data of PRC coupling beams at home and abroad.

The influence factors of the deformation capacity of PRC coupling beams are mainly related to the span-to-depth ratio l_n/h, the stirrups reinforcement ratio ρ_t, plate characteristic values $\lambda_p[\lambda_p=(A_pf_p)/(b_{h0}f_c)]$, reinforcement characteristic values $\lambda_s[\lambda_s=(A_sf_y)/(b_{h0}f_c)]$. Figs. 12-15 the influence of these four factors on the deformation

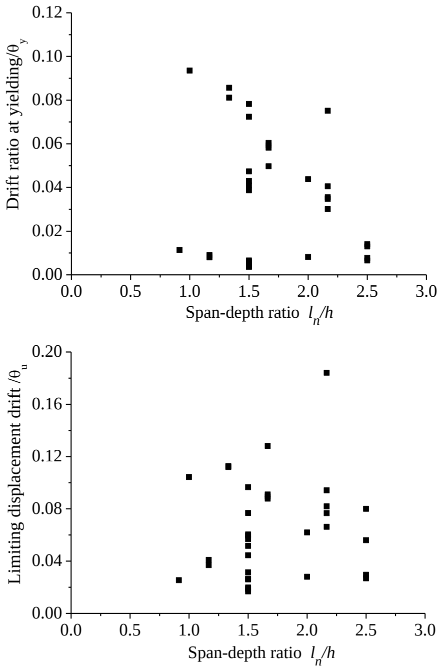


Fig. 12 Effect of span-to-depth ratio l_n/h on displacement angle of PRC coupling beam

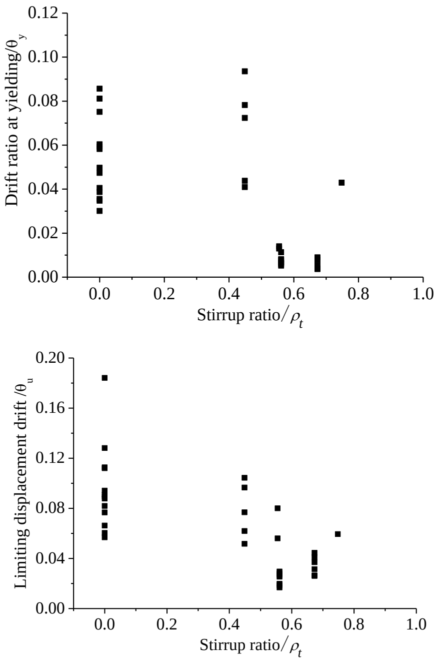


Fig. 13 Effect of stirrups reinforcement ratio ρ_t on the displacement angle of PRC coupling beam

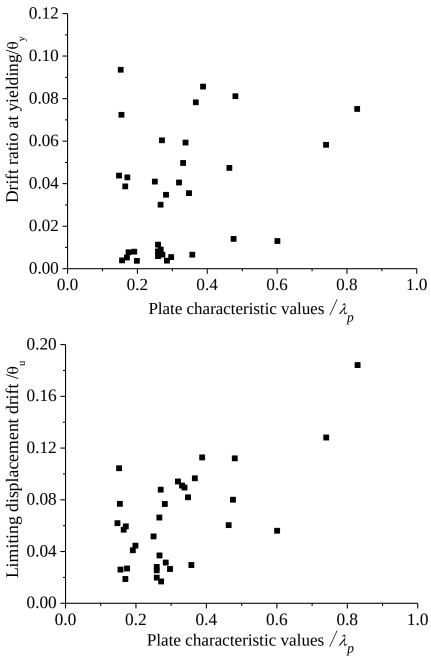


Fig. 14 Effect of plate characteristic values λ_p on the displacement angle of PRC coupling beam

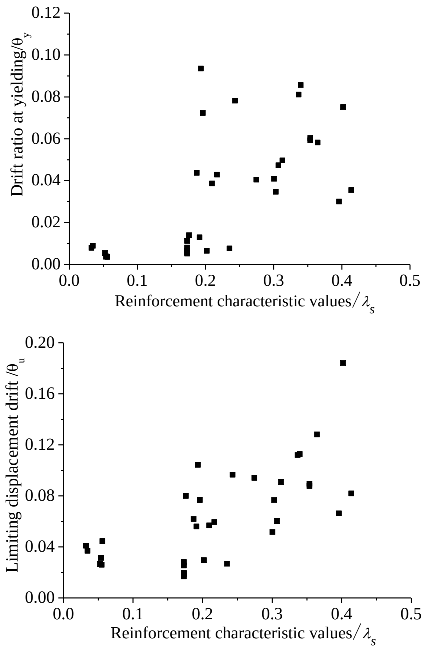


Fig. 15 Effect of reinforcement characteristic values λ_s on the displacement angle of PRC coupling beam

performance of PRC coupling beam is given.

By regression analysis of the test data and considering that the λ_p of the PRC coupling beam is not less than 0.16, and when the displacement angle demand is $\theta_{u,dem}$, the suggested formula of plate characteristic value λ_p is

$$\lambda_p = \max\left\{0.65\theta_{u,dem}\lambda_s\rho_t/\left(l_n/h\right)+5.72\theta_{u,dem}-0.12, 0.16\right\} \quad (18)$$

In the formula, λ_s is the reinforcement characteristic value of the coupling beam, ρ_t is the stirrups reinforcement ratio of the coupling beam, and the l_n/h is the span-to-depth ratio of the beam.

7. Seismic performance control method of PRC coupling beam-hybrid coupled shear wall system

7.1 Section dimensions control of coupling beam

In the 2 section, a fitting formula of the coupling ratio

(CR) for the coupled wall under the action of the continuum method under inverted triangular horizontal load is as follows

$$CR = \frac{3T}{\alpha^2}\left[\frac{\alpha^2}{3} - \text{ch}\alpha + (\text{sh}\alpha - \frac{\alpha}{2} + \frac{1}{\alpha})\text{th}\alpha\right] \tag{19}$$

According to the target coupling ratio, the integrative coefficient α of the shear wall can be determined by Eq. (19), then under the conditions given in the wall-section dimensions, the section dimensions of the coupling beam can be determined according to the following formula

$$\alpha = H\sqrt{\frac{6\tilde{I}_b c^2}{ha^3(I_1+I_2)}\left(\frac{I}{I-I_1-I_2}\right)} \tag{20}$$

In the formula, $I=I_1+I_2+2A_1c^2+2A_2c^2$,

For a symmetric hybrid coupled shear wall with rectangular section, $A_1=A_2$ is obtained, and Eq. (20) can be rewritten as

$$\alpha = \sqrt{Hn\frac{3\tilde{I}_b c^2}{2a^3(1-T)I}\cdot\frac{I}{A_1 c^2}} \tag{21}$$

When the shear deformation of the coupling beam is neglected, $\tilde{I}_b=I_b=\frac{t_b h_b^3}{12}$, then the following formula can be obtained from Eq. (21)

$$\alpha = \sqrt{Hn\frac{t_b}{\lambda^3 A_1}\cdot\left(\frac{1}{1-T}\right)} \tag{22}$$

When the shear deformation of the coupling beam is considered, $\tilde{I}_b=\frac{I_b}{1+\frac{7.5\mu I_b}{A_b a^2}}$, then the following formula can be obtained from Eq. (21)

$$\alpha = \sqrt{Hn\frac{t_b}{\lambda^3 A_1}\cdot\left(\frac{1}{1-T}\right)\cdot\frac{1}{1+3/\lambda^2}} \tag{23}$$

In the formula, $\lambda=2a/h_b$, it is the calculated span-to-depth ratio of coupling beams.

If the coupling beam and wall thickness equal, such that $\lambda_H=H/h_w$, h_w is the wall section height, then

$$\alpha = \sqrt{n\frac{\lambda_H}{\lambda^3}\cdot\left(\frac{1}{1-T}\right)\cdot\frac{1}{1+3/\lambda^2}} \tag{24}$$

For the rectangular section coupled wall, the thickness and height of wall section are the thickness and height of the original section in Eqs. (20)-(24). For *T*-shaped and *L*-shaped, the flexural rigidity of the original section and the position of the centroidal axis remain unchanged to determine the thickness and height of the equivalent rectangular section.

7.2 Determination of base shear

Under the action of inverted triangle horizontal load, the differential equation of the coupled shear wall and its solution are

$$\Phi^{*}(\xi) - \alpha^2\Phi(\xi) = -\alpha^2\left[1-(1-\xi)^2\right] \tag{25}$$

$$\Phi(\xi) = 1-(1-\xi)^2 + \left[\frac{2\text{sh}\alpha}{\alpha} - 1 + \frac{2}{\alpha^2}\right]\frac{\text{ch}\alpha\xi}{\text{ch}\alpha} - \frac{2}{\alpha}\text{sh}\alpha\xi - \frac{2}{\alpha^2} \tag{26}$$

The relationship between the variables $\Phi(\xi)$ and the line restraining moment of the coupling beam $m(\xi)$ in the Eq. (26) is

$$\Phi(\xi) = m(\xi)\cdot\frac{\alpha^2}{\alpha_1^2}\cdot\frac{1}{V_0} \tag{27}$$

In the formula, V_0 is the total shear force at the bottom of the structure.

Under inverted triangular horizontal load, the lateral displacement at any height of the coupled shear wall is

$$\begin{aligned} y = {} & \frac{V_0H^3}{60E\sum I_i}(1-T)(11-15\xi+5\xi^4-\xi^5) + \frac{\mu V_0 H}{G\sum A_i}\left[(1-\xi)^2 - \frac{1}{3}(1-\xi^3)\right] \\ & -\frac{TV_0H^3}{E\sum I_i}\left\{C_1\frac{1}{\alpha^3}\left[\text{sh}\alpha\xi + (1-\xi)\alpha\text{ch}\alpha - \text{sh}\alpha\right]\right. \\ & +C_2\frac{1}{\alpha^3}\left[\text{ch}\alpha\xi + (1-\xi)\alpha\text{sh}\alpha - \text{ch}\alpha - \frac{1}{2}\alpha^2\xi^2 + \alpha^2\xi - \frac{1}{2}\alpha^2\right] \\ & \left. -\frac{1}{3\alpha^2}(2-3\xi+\xi^2)\right\} \end{aligned} \tag{28}$$

In the formula, $\xi=x/H$, $T=\frac{\alpha_1^2}{\alpha^2}$, $C_1=-\left[\left(1-\frac{2}{\alpha^2}\right)-\frac{2sh\alpha}{\alpha}\right]\frac{1}{ch\alpha}$, $C_2=-\frac{2}{\alpha}$.

When $\xi = 0$, the top horizontal displacement of the coupled shear wall can be obtained as

$$\Delta = \frac{11}{120}\frac{qH^4}{E\sum I_i}\left[1+3.64\gamma^2 - T + \varphi_a T\right] \tag{29}$$

In the formula

$$\gamma^2 = \frac{\mu E\sum I_i}{H^2 G\sum A_i} \tag{30}$$

$$\varphi_a = \frac{60}{11}\frac{1}{\alpha^2}\left(\frac{2}{3} + \frac{2\text{sh}\alpha}{\alpha^3\text{ch}\alpha} - \frac{2}{\alpha^2\text{ch}\alpha} - \frac{\text{sh}\alpha}{\alpha\text{ch}\alpha}\right) \tag{31}$$

Given the limit value $\theta_{\lim}$ of the elastic layer lateral displacement angle of the shear wall, if it is assumed that the structural stiffness is uniformly distributed along the height, the limit value of the elastic lateral displacement angle of the top of the shear wall can be approximately taken as $\theta_{\lim}$. According to the code for seismic design of buildings (GB50011-2010), $\theta_{\lim}$=1/1000, From Eq. (29) calculated inverted triangular distribution of the maximum set of degrees q. Use the Eq. (28) to calculate the lateral displacement y_i of each layer of the structure and calculate the story displacement Δ_i; if the maximum story displacement $\Delta_{max}>h\theta_{\lim}$ (h is the height of the layer), q should be amended as

$$q_1 = q\frac{h/1000}{\Delta_{\max}} \tag{32}$$

This is to ensure that the story displacement angle and the lateral displacement of the top of the coupled shear wall structure do not exceed the limit value $\theta_{\lim}$ of the elastic layer lateral displacement angle. Correspondingly, the bottom total shear that satisfies the structural lateral displacement angle limit is

$$V_0^a = \frac{1}{2} q_1 H \quad (33)$$

In order to prevent the shear wall structure from being too rigid, the base shear force of the shear wall structure according to Eq. (33) should not exceed the shear force of the foundation obtained from the Code for Seismic Design of Buildings (GB50011-2010).

$$V_0^e = F_{Ek} = \alpha_1 G_{eq} \quad (34)$$

In the formula, α_1 is the seismic influence coefficient corresponding to the fundamental period of the shear wall structure, and G_{eq} is the equivalent total gravity load of the coupled shear wall structure.

The fundamental period of the coupled shear wall structure can be calculated as follows

$$T_1 = 1.7 \psi_T \sqrt{u_T} \quad (35)$$

In the formula, u_T represents the hypothetical lateral displacement of the structure vertex, that is, the vertex lateral displacement (m) obtained by applying the representative gravity value of each layer to each particle; and ψ_T represents the periodic reduction coefficient considering the influence of the non-load-bearing wall.

7.3 PRC coupling beam embedded plate size determination

By means of the continuous connection method, the relative displacement $\Delta(\xi)$ at both ends of the coupling beam can be obtained as

$$\Delta(\xi) = \frac{ha^3}{3E\tilde{I}_b} \frac{V_0}{c} T \cdot \Phi(\xi) \quad (36)$$

Eq. (36) calculates the maximum relative displacements at both ends of all beams with Δ_{max}^{cb}. Given the required beam displacement ductility for the μ_b, then the relative displacement at both ends of the beam relative maximum displacement of Δ_{max}^{cb} corresponding bowstring chord θ_{max}^{cb}

$$\theta_{\max}^{cb} = \mu_b \frac{\Delta_{\max}^{cb}}{l_b} \quad (37)$$

According to the target coupling ratio *CR*, assuming that each coupling beam to bear the same shear force, then the shear carrying capacity V_b beam determined by the following formula

$$\sum_{i=1}^{n} V_{bi} = \frac{CR \times M_0}{l_w} \quad (38)$$

$$V_b = \frac{\sum_{i=1}^{n} V_{bi}}{n} \quad (39)$$

In the formula, M_0 represents the total overturning moment at the bottom of the structure; $\sum_{i=1}^{n} V_{bi}$ represents the vertical shear force of all beams, *n* represents the total number of coupling beams along the height of the structure.

Assuming that the inflection point is at the midpoint of its net span, the moment at the beam side can be obtained from the shear of the coupling beam.

According to the above-mentioned PRC coupling beam experiment and FEM analysis, it is suggested that the height of the steel plate embedded in the PRC beam is not less than 70% of the height of the section. In order to make the steel plate participate in the shearing as much as possible, it is recommended that the maximum depth-thickness ratio (h_p/t_p) should not be more than 100, and taking into account the actual construction and other factors, steel thickness t_p should not be less than 6 mm.

According to the requirement of longitudinal reinforcement ratio and the height requirement of steel plate, the longitudinal reinforcement ratio and the steel plate section height can be presumed. The size of steel plate embedded in PRC coupling beams should meet the requirements of shear capacity. The publication (Tian *et al*. 2016) determine the thickness of the embedded plate t_{p1}.

According to the requirement of displacement angle θ_{max}^{cb} of PRC coupling beam, stirrups reinforcement ratio ρ_t, span-to-depth ratio l_n/h and reinforcement characteristic λ_s, the plate characteristic values λ_p can be calculated according to Eq. (18), further determining the thickness of the embedded steel plate t_{p2}

$$t_{p2} = \frac{\lambda_p b h_0 f_c}{f_p h_w} \quad (40)$$

Comparing the plate thickness t_{p1} determined by the shear carrying capacity control of the coupling beam with the plate thickness t_{p2} determined by the calculation of the control requirements of the displacement of the coupling beam, the thickness of the steel plate embedded in the PRC finally joins the larger of t_{p1} and t_{p2}.

7.4 Analysis step of control method for seismic performance of PRC coupling beam-hybrid coupled shear wall system

To sum up, based on the continuous connection method, this chapter is based on the reasonable coupling ratio of the shear wall, the limit value of the interlayer displacement angle and the ductility demand of the PRC coupling beam. Fortification seismic intensity moderate damage, more severe damage under the effect of rare earthquake as a performance target, proposed PRC coupling beam–hybrid coupled shear wall system seismic performance control methods.

The analysis steps are as follows: first, the sectional size of PRC coupling beams is determined according to the height, number of layers, sectional dimensions, material properties and the coupling ratio *CR* that meets the requirements of the integral shear wall. Further, it is assumed that the base shear force is determined by controlling the vertex and the lateral shift angle of the coupled shear wall structure under the action of the inverted triangular horizontal distribution load. At last, we determine the demand of turn angle for coupling beam to meet the demand of displacement ductility, and determine the size of

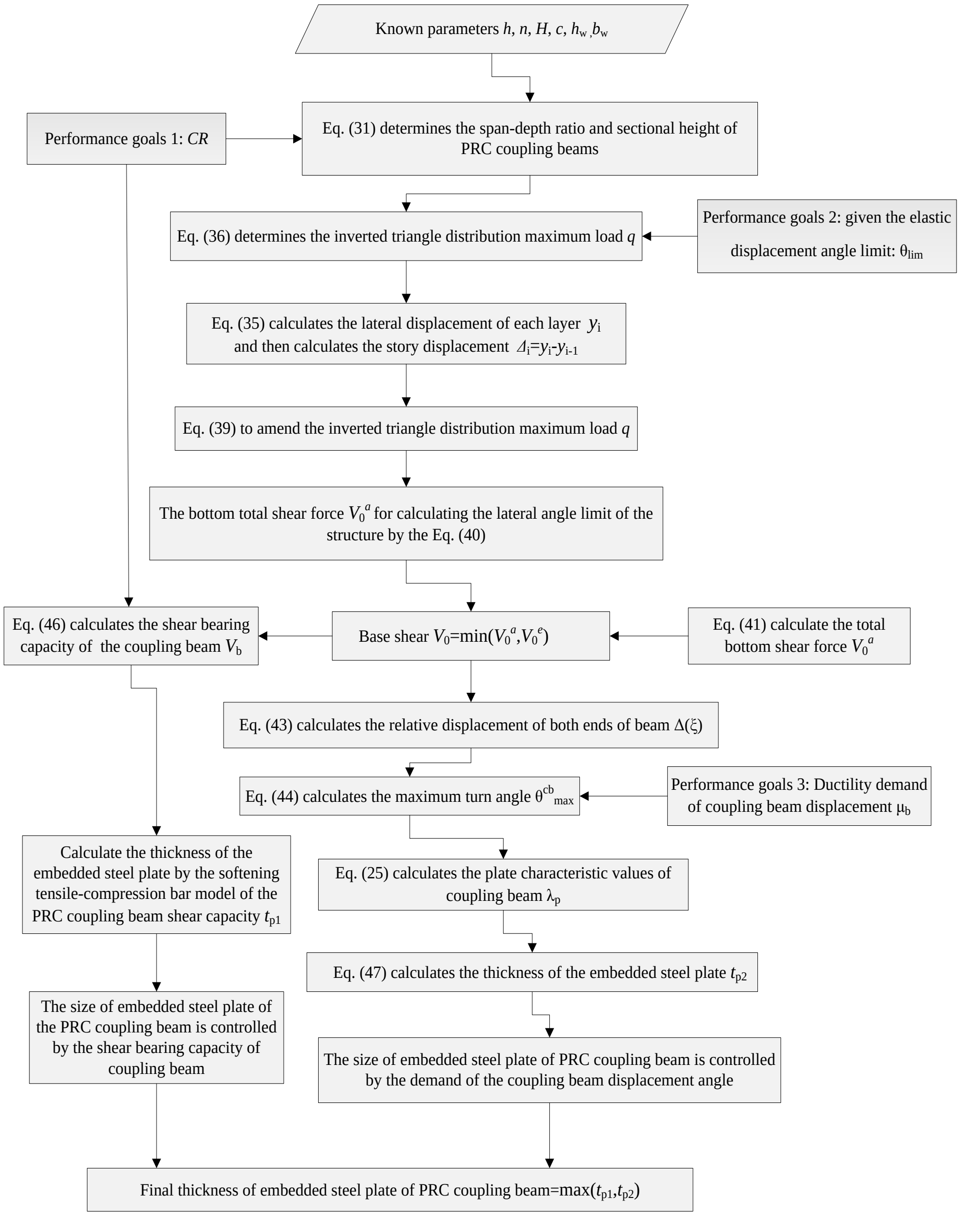


Fig. 16 Seismic performance control calculation flow chart of PRC coupling beam–hybrid coupled shear wall system

the embedded steel plate required by PRC coupling beam according to the relative vertical deformation demand at both ends of the coupling beam, and the size of the embedded steel plate of PRC coupling beam should meet the shear carrying capacity requirement. Detailed analysis steps are shown in Fig. 16.

7.5 Example and its analysis

Take an 11-layer symmetrical coupled shear wall as an example to illustrate the above design method. The structure layer is h=3.3 m, wall height H=36.3 m, wall section dimensions shown in Fig. 17. Wall piers and even the thickness of the coupling beam are taken 0.3 m, concrete strength grade C40, longitudinally reinforcement for the HRB400, coupling beam stirrup HPB300, coupling beam embedded steel Q235. The structure is located at the 8th degree fortification zone and Class Ⅱ site. The design

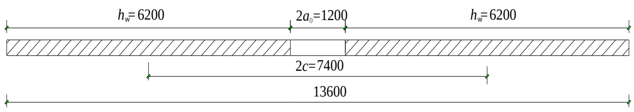


Fig. 17 Example analysis of the sectional shear wall schematic

seismic group is the second group with T_g=0.4s and the representative gravity load values of all layers are 2400 kN.

1) According to the total number of structural layers n=11, the height of the wall members H=36.3 m, the height of the wall members h_w=6.2 m, the clear span of coupling beams $2a_0$=1.2 m, given the target coupling ratio CR=0.5, Eq. (24) initially determined that the span-to-depth ratio is 2 and the corresponding section height is 600mm.

2) According to Code for Design of Seismic Design of Buildings (GB50011-2010), take the elastic limit of the top of the shear wall structure as θ_{lim}=1/1000, take $y(H)$=0.0363

m, Eqs. (30)-(31) calculated φ_a=0.0918, γ_2=0.0073, obtained by the Eq. (29) inverted triangular distribution maximum load concentration q=304.03 kN/m.

3) According to the q value calculated above, calculate the lateral displacement of each layer by Eq. (28), then further calculate the lateral displacement of each layer, and the maximum story displacement occurs in the eighth layer, that is, $\Delta_{max}=\Delta_8=y_8-y_7$=0.00370 m. The lateral displacement, story displacement, lateral displacement angle and the deformation of the coupling beam of each layer of the coupled wall are shown in Table 6.

4) It can be seen from Table 6 that the maximum lateral displacement $\Delta_{max}>h/1000$ obtained in step (3) is maximized by the inverse triangular distribution obtained in step (2) from Eq. (32) set of degrees q amended to

$$q_1 = q\frac{h/1000}{\Delta_{max}} = 270.96\text{kN}$$

The bottom total shear force that satisfies the structural drift angle limit is

$$V_0^a = \frac{1}{2}q_1 H = 4917.89\text{kN}$$

5) The representative value of gravity load at each level of the structure acts on each mass point, and the lateral displacement u_T=0.1447 m of the structure is calculated. From the Eq. (35), the fundamental period T_1=0.647s of coupled shear wall structure, T_g=0.4s, α_{max}=0.16, then

$$\alpha_1 = \left(\frac{T_g}{T_1}\right)^{0.9}\alpha_{max} = 0.104$$

Available from Eq. (34)

$$V_0^e = F_{Ek} = \alpha_1 G_{eq} = 2330.09\text{kN}$$

Because of $V_0^e < V_0^a$, so the base shear force V_0=2330.09 kN, with the adjusted base shear to calculate the lateral displacement and the corresponding lateral displacement angle, the results shown in Table 6.

6) The relative displacement $\Delta(\xi)$ between the two ends of the beam is calculated by the Eq. (36). From the Eq. (37), the tangent angle θ_{max}^{cb} of the coupling beam corresponding to the maximum value of the relative displacement at both ends of the coupling beam is

$$\theta_{max}^{cb} = \mu_b\frac{\Delta_{max}^{cb}}{l_b} = 0.49\%$$

The tangent angle of the beam of each layer is shown in Table 6.

7) Select the target coupling ratio CR=0.5 according to the total overturning moment at the bottom of the earthquake calculation structure, and calculate the shear force of each coupling beam by Eq. (39) as follows

$$M_0 = \frac{2}{3}V_0 H = 56388.09\text{kN}\cdot\text{m}$$

$$\sum_{i=1}^{n} V_{bi} = \frac{CR\times M_0}{l_w} = 3810.01\text{kN}$$

$$V_b = \frac{\sum_{i=1}^{n} V_{bi}}{n} = 346.36\text{kN}$$

8) Suppose that the longitudinal reinforcement of beam is 2C28, $A_s = A'_s = 1232mm^2$, f_y=360 N/mm^2, the thickness of concrete cover is 40mm, the width of beam is 250mm, the height of section is 600 mm, the effective height of beam is h_0=540 mm, concrete strength grade C40, f_c=19.1 N/mm^2, reinforcing characteristic value λ_s=0.137. For PRC coupling beams, stirrups 2A8@100 were configured according to the structure. The stirrup rate ρ_t=0.40% and f_{yt}=270 N/mm^2. Take steel plate to embed stirrup internal spacing of 15 mm, the steel section height is determined as follows

$$H_p = 600-40-40-8-8-15 = 489 \text{ mm}$$

Take the plate height h_p=480 mm, and h_p/h=480/600=0.8>0.7, assuming the thickness of the steel t_p<16 mm, then the f_{yp}=215 N/mm^2.

The size of embedded steel plate should meet the requirements of shear capacity, and the calculation formula from Tian *et al*. (2016) of simplified softened tension-compression rod model is adopted, thickness $t_{p1} \geq 5.62mm$, take the thickness of steel plate t_{p1}=6 mm.

9) According to the requirement of displacement angle of PRC coupling beam θ_{max}^{cb}, stirrups reinforcement ratio ρ_t, span-to-depth ratio l_n/h and reinforcement characteristic λ_s, the characteristic value λ_p can be calculated according to Eq. (18) which is

$$\lambda_p = \max\left\{0.65\theta_{u,dem}\lambda_s\rho_t/\left(l_n/h\right) + 5.72\theta_{u,dem} - 0.12, 0.16\right\} = 0.16$$

The thickness of embedded steel t_{p2} is: $t_{p2} = \frac{\lambda_p b h_0 f_c}{f_p h_w} = 4.80$ mm

Therefore, in this case, the size of the steel plate embedded in the PRC beam is controlled by the carrying capacity of the seismic shear, and finally the thickness of the steel plate embedded in the PRC beam is t_p= 6 mm.

Steel anchorage length l_a should meet

$$1.14\times 600 = 684\text{mm} \leq l_a \leq 2\times 600 = 1200m$$

Therefore, the anchorage length of steel plate l_a=700 mm, the arrangement of shear studs can be set according to the technical requirements of the structure of steel reinforced concrete. The detailed configuration of PRC beams is shown in Table 7.

8. Conclusions

Based on the research results of PRC coupling beam specimen, this paper designs the BS Basic model specimen of PRC coupling beam-hybrid coupled shear wall system, uses the Abaqus finite element software to simulate the seismic performance of PRC coupling beam-hybrid shear wall system, mainly studies the coupling rate, the section size of the beam, the aspect ratio of the single wall, and this paper studies the control and design methods of the seismic behavior of PRC coupling beam-hybrid coupled shear wall system. The conclusions are as follows:

- The bearing capacity and ductility of PRC coupling beam-hybrid shear wall system considering the effect of floor slab is higher than that of PRC coupling beam-hybrid coupled shear wall system, which does not consider the role of floor slab. It is suggested that the role of longitudinal reinforcement should be considered in the design of PRC coupling beam-hybrid shear wall system, so that its bearing capacity and ductility can be guaranteed.

• The coupling rate of the coupled shear wall is through the section size of the PRC coupling beam, the result shows that the coupling rate affects not only the failure law of shear wall and the development order of plastic hinge, but also the main factors that affect the bearing capacity and ductility of the structure. The coupling rate can reflect the overall seismic performance of the hybrid coupled shear wall structure, the coupling rate can not be too large or too small, it is suggested that the reasonable coupling rate of PRC coupling beam-hybrid coupled shear wall system in the high seismic fortification zone is 40%~60%.

• A fitting formula of plate characteristic values for PRC coupling beams based on different displacement requirements is proposed through the experimental data regression analysis of PRC coupling beams at home and abroad. The seismic behavior control method for PRC coupling beam-hybrid coupled shear wall system is proposed based on the continuous connection method and through controlling the coupling ratio, the roof displacement, story drift angle of hybrid coupled shear wall system, displacement ductility of coupling beam.

Acknowledgements

The work reported in this paper was supported by the National Natural Science Foundation of China (Grant No. 51608441), China Postdoctoral Science Foundation (Grant No. 2017M613174), Natural Science Basic Research Plan in Shaanxi Province of China (Grant No. 2017JQ5032) and Young Talent fund of University Association for Science and Technology in Shaanxi, China (Grant No. 20170513). The authors express their sincere gratitude to the sponsors.

References

CEP-FIP Model Code 90 (1993), Model Code for Concrete Structures, Thomas Telford, London, UK.

Cheng, M.Y., Fikri, R. and Chen, C.C. (2014), "Experimental study of reinforced concrete and hybrid coupled shear wall systems", *Eng. Struct.*, **82**, 214-225.

GB50011-2010 (2010), Code for Seismic Design of Buildings, China Architecture Industry Press, Beijing, China.

Gong, B. and Shahrooz, B.M. (2001), "Steel-concrete composite coupling beams-behavior and design", *Eng. Struct.*, **23**(11), 1480-1490.

Harries, K.A. and EERI, M. (2001), "Ductility and deformability of coupling beams in reinforced concrete shear walls", *Earthq. Spectra*, **17**(3), 457-478.

Harries, K.A., EERI, M., Gong, B. and Shahrooz, B.M. (2000), "Behavior and design of reinforced concrete, steel, and steel-concrete coupling beams", *Earthq. Spectra*, **16**(4), 775-799.

Harries, K.A., Mitchell, D., Redwood, R.G. and Cook, W.D. (1998), "Nonlinear seismic response predictions of walls coupled with steel and concrete beams", *Can. J. Civil Eng.*, **25**(5), 803-818.

Hou, W., Xu, S.L., Ji, D.S., Li, Q.H. and Lin, G. (2018), "Cyclic performance of steel plate-reinforced high toughness-concrete coupling beams with different span-to-depth ratios", *J. Struct. Eng.*, **144**(10), 1-11.

Hou, W., Xu, S.L., Ji, D.S., Li, Q.H. and Zhang, P. (2019), "Seismic performance of steel plate reinforced high toughness concrete coupling beams with different steel plate ratios", *Compos. Part B: Eng.*, **159**(15), 199-210.

Huang, D.S., Cheng, W.X. and Peng, F. (2005), "Low-cycle loading experiment study on symmetric double short-pier shear walls", *J. Build. Struct.*, **26**(3), 51-56.

Hung, C.C. and Lu, W.T. (2015), "Towards achieving the desired seismic performance for hybrid coupled structural walls", *Earthq. Struct.*, **9**(6), 1251-1272.

Saenz, L.P. (1964), "Discussion of equation for the stress-strain curve of concrete by Desayi and Krishnan", *ACI Struct. J.*, **61**(9), 1229-1235.

Seongwoo, G., Myoungsu, S., Benjamin, P. and Deokjung, L. (2014), "Nonlinear modeling parameters of RC coupling beams in a coupled wall system", *Earthq. Struct.*, **7**(5), 817-842.

Shahrooz, B.M., Remmetter, M.E. and Qin, F. (1993), "Seismic design and performance of composite coupled walls", *J. Struct. Eng.*, **119**(11), 3291-3309.

Su, R.K.L., Lam, W.Y. and Pam, H.J. (2008), "Behavior of embedded steel plate in composite coupling beams", *J. Constr. Steel Res.*, **64**(10), 1112-1128.

Tian, J.B., Shi, Q.X., Wang, N., Wang, P. and Pan, X.Z. (2016), "Analysis of shear capacity of steel-concrete composite coupling beams with small span and height ratio based on softened tension-compression bar model", *Eng. Mech.*, **33**(5), 142-149.

Wang, P., Shi, Q.X., Wang, F. and Wang, Q.W. (2017), "Experimental investigation of SRHSC columns under biaxial loading", *Earthq. Struct.*, **13**(5), 485-496.

CC