RESEARCH ON DEFORMATION BEHAVIOR OF REINFORCED CONCRETE COMPOSITE SHEAR WALL WITH CONCEALED BRACINGS BASED ON PERFORMAMCE

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Abstract:

In order to determine the deformation capacity of reinforced concrete composite shear wall with concealed bracings at different performance levels, some previous research of domestic scholars are reviewed by analyzing 89 shear wall specimens using a performance-based seismic design method. The performance levels of the structural element are divided into three stages to comply with the code for seismic design of buildings in China. Meanwhile, sectional plastic displacement angle under each performance level is derived and fitted within the shear span ratio ranging from 1-3. The analysis results show that average values of plastic displacement angle are about 2-3 times the corresponding ordinary shear wall, so we propose security reserve value K, as well as performance indexes of shear wall with concealed bracings according to the test data. Finally, indexes are compared with the relevant norms to provide references for China seismic design.

1 Introduction

Shear wall becomes the main component of high-rise structure to resist seismic force because of its large lateral stiffness. As the first line of defense, however, when earthquake comes, the brittle failure often occurs in ordinary shear wall. This kind of situation is usually caused by poor ductility and energy dissipation capacity of shear wall itself. Therefore, improving the seismic behavior of shear wall becomes the key issue in high-rise seismic technology. Professor Cao W.L. of Beijing University of Technology proposed a composite shear wall with concealed bracings [1] , of which the reinforced support or steel truss are hidden in the reinforced concrete , as shown in Fig.1.

The composite shear wall combines two different materials and structural forms, to overcome the traditional shear wall shortcomings of poor deformation capacity, and it greatly improves the seismic performance of high-rise structure. Chinese current seismic code is based on the design method of bearing capacity, and this approach has a certain degree in ensuring the safety of life, which is also being adopted by many other countries at present. However, with the development of city, a lot of good facilities or highly invested buildings have suffered great economic losses due to severe structural damage so that even casualties are small under the

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earthquake. So, in the 1990s, researchers proposed performance-based seismic design method [2,3], namely, the structure can achieve different performance levels at different predetermined usage demands, and it can be quantitatively designed concerning the requirement for wall design with emphasis on deformation of shear wall.

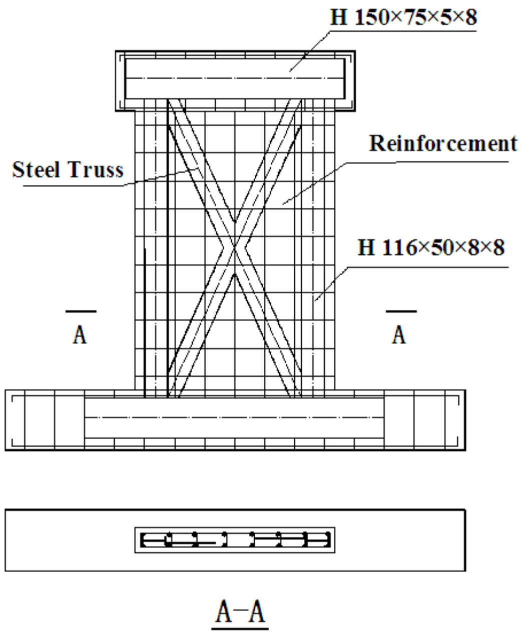

Figure 1. Composite shear wall with concealed steel bracings.

Professor Cao W.L. put forward seismic shear wall with concealed bracings in 1998, then he did a series of analysis and some experimental research. Literature [4] accomplished two models of composite mid-rise shear walls with concrete filled steel tube columns under low frequency circle load, and its shear span ratio is 1.5. In Literature [5], special-shaped (including blade-shaped, T-shaped, L-shaped and Z-shaped) short-pier shear wall specimens were designed and tested under cyclic loading to assess their seismic performance. Literature [6] conducted an experimental study on seismic performance of shear wall models with opening and single row of steel bars. Literature [7] studied the seismic behavior of three shear walls, including a shear wall with steel frame, a shear wall with steel truss and a usual one, etc. The abovementioned analyses show that: ultimate bearing capacity, yield strength and ductility factor of concealed bracing shear wall have different increasing degrees compared with the ordinary reinforced concrete shear wall, in particular its energy dissipation ability has significantly improved so that it reflects the excellent seismic performance. Therefore, this work will be of great value to study.

The FEMA356 [8] and the ASCE41 [9] specifications of America present component's limits of performance index, while in Chinese *Code for Seismic Design of Buildings GB50011-2010* [10], deformation capacity of component is ensured by means of structural measures. Therefore, in order to predict and assess the seismic response of concealed bracings shear wall components better and to further explore their deformation properties, we propose this performance-based seismic theory for shear wall design. This paper analyses the ductility of 89 concealed bracings shear walls at different performance states, deduces and quantifies cross-section plastic displacement angles, and then makes reasonable limit values.

2 Performance level and classification

Performance levels of the structural members are divided into OP, IO, LS and CP four stages in the FEMA356 specification, as shown in Fig.2, i.e., Operational, Immediate Occupancy, Life Safety and Collapse Prevention. It is shown that the OP state corresponding to the component may crack when in good condition; in the IO state corresponding to the structure, damage may occur, but the basic function is not affected; the LS state corresponding to the main structure has a heavier damage but does not affect the load bearing; the CP state corresponding to the main structure has serious damage, but does not collapse.

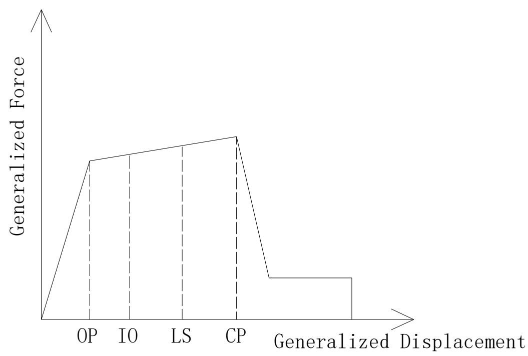

Figure 2. Performance levels of specimens.

However, Chinese *code for seismic design of buildings* uses three levels of seismic fortification target. Its basic seismic fortification goals are: when subjected to frequent earthquake effect which is below the local seismic fortification intensity, the main structure is not damaged or there is no need to

repair, and it can continue to be used ;When subjected to equivalent to the local seismic fortification intensity effect, the structure damage may occur, but it can still continue to be used throughout general repair; When subjected to rarely met earthquake effect which is higher than the local seismic fortification intensity, the structure will not collapse neither life-threatening serious damage occurs. Namely, ‘not destroyed during small earthquakes repairable under moderate earthquakes, it does not collapse in severe earthquake’. When using performance-based seismic design, it has more specific and higher seismic fortification goals.
According to the basic idea of performance-based seismic design method, we convert performance indexes defined by FEMA356 into the corresponding performance indexes in line with Chinese seismic code requirements, which means that component performance indexes corresponding to three level requirements of seismic fortification are: small earthquake index, moderate earthquake index and severe earthquake index. The performance indexes between Chinese code and the FEMA356 are shown in Table1.

Table1. Comparison of performance states based on Chinese code and FEMA 356

State	FEMA356 index	Chinese seismic level
Elastic	OP	
Close to yield	IO	small earthquake
Yield not collapse	LS	moderate earthquake
Close to collapse	CP	severe earthquake

3 Quantitative values of cross-section plastic displacement angles

Quantitative performance indexes of the structure usually have three physical quantities: force, displacement and energy. The damage status of the structure is always closely related to the deformation of the cross section, and the cross section deformation can be described by the plastic displacement angle, thus the design method based on the cross-section plastic displacement angle is an important approach to realization of a performance-based design. This paper collects 89 pieces of shear walls with concealed bracings [11-42], the test data of which are analyzed. The parameters of shear wall specimens are shown in Table 2. Under cyclic loading, deformations of the specimens are greatly influenced by shear span ratio. Domestic experts often determine the failure modes of shear wall based on the scope of shear span ratio at preliminary judging so that a plastic displacement angle is fitting to a formula of shear span ratio. Since OP state is in elastic stage, there is no need to determine its performance goal, so we calculate plastic displacement angles of IO, LS and CP state. When calculating the shear wall sectional curvature, in order to simplify the calculation, we use following assumptions: (1) The average strain of shear wall section accords with the plane section assumption; (2) Tensile force of concrete in tension zone will not be considered; (3) The bond slip between steel and concrete will not be taken into account.

3.1 Cross-section plastic displacement angle of IO state

The cross-section plastic displacement angle of IO state is calculated according to approximate yield status. When longitudinal reinforced strain in the tensile area of shear wall cross-section reaches the yield strain, it is defined as the section achieving yield limit state. At this point, the section yield curvature ϕ_y is:

$$\phi_y = \frac{\varepsilon_y}{h_{wo} - x} \tag{1}$$

Where ε_y is for yield strain of tensile longitudinal reinforcement of edge; h_{wo} is for the effective height of shear wall cross-section; x is for the height of compressive zone. Priestley [43] believed that the section yield curvature of shear wall ϕ_y only relates to yield strain of tensile longitudinal reinforcement ε_y and the effective height of shear wall section h_{wo}, namely:

$$\phi_y = \alpha \frac{\varepsilon_y}{h_{wo}} = \alpha \frac{f_y}{E_s h_{wo}} \tag{2}$$

where α is undetermined coefficient; f_y stands for the yield strength of tensile longitudinal reinforcement of edge; E_s stands for the elastic modulus of tensile longitudinal edge reinforcement. For shear wall without holes, its stress pattern is similar to a cantilever bar. In the calculation of yield displacement and ultimate displacement of shear wall, the wall can be simplified as a cantilever bar.

Table 2. Parameters of specimens

Concrete strength grade							
Strength/ MPA	C20	C25	C30	C35	C40	C50	C60
Number of specimens	11	9	19	34	6	6	4
Specimens with shear span ratio distribution							
shear span ratio	< 1.5		1.5-2.0		>2.0		
Number of specimens	25		40		24		
Specimens with axial pressure ratio distribution							
Axial pressure ratio	0.2-0.3		0.3-0.5		0.5-0.7		
Number of specimens	67		8		14		
Specimens with edge constraint distribution							
Constraint	Side columns		Embedded columns		Flange columns		
Number of specimens	34		50		5		

When the shear wall bottom section just yield, it can be considered that curvature is linear distribution along with the wall height, so yield displacement at the top of shear wall Δ_y is available:

$$\Delta_y = \frac{1}{3}\phi_y H^2 \tag{3}$$

where H is the height of shear wall .
Then the cross-section displacement angle is:

$$\theta_y = \frac{1}{3}\phi_y H \tag{4}$$

Applying the equation (2) to the equation (4), it is obtained:

$$\theta_y = \frac{1}{3}\alpha \frac{f_y H}{E_s h_{wo}} = \beta_1 \frac{f_y H}{E_s h_{wo}} \tag{5}$$

where β_1 is an undetermined coefficient.
So, the shear wall plastic displacement angle under the condition of IO θ_{IO} is:

$$\theta_{IO} = \theta_y = \beta_1 \frac{f_y H}{E_s h_{wo}} \tag{6}$$

Through analysis of test data of about 89 pieces of concealed bracings shear walls, and taking the discrete data and safety reasons into account, the envelope of data is fitted approximately, as shown in Fig.3.

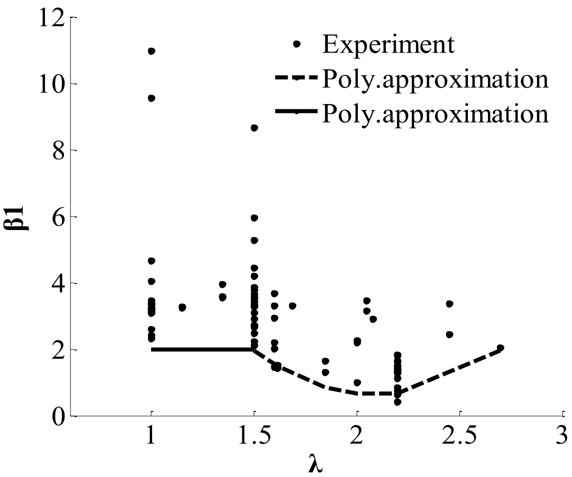

Figure 3. Relationship between the coefficient β_1 and shear span ratio λ.

When $1 \leq \lambda < 1.5$, almost all the coefficients β_1 are greater than 2, so $\beta_1(\lambda) = 2$;
When $1.5 \leq \lambda < 3$, the coefficients β_1 appear to be increasing after being decreasing, so it is fitted as quadratic function:

$$\beta_1(\lambda) = 3.6659\lambda^2 - 15.3758\lambda + 16.7576$$

After comparing fitted values with experimental calculated ones, the fitting method has guaranteed rate of 96.6%.

3.2 Cross-section plastic displacement angle of LS state

In the LS state, the shear wall has entered the elastic-plastic stage and produced a certain length of plastic displacement hinge at the bottom. At the edge of the compression zone of shear wall, if concrete compressive strain attains peak strain ε_c, then shear wall section achieves the maximum bearing capacity which reaches the LS state. In this case, the corresponding cross-section peak curvature ϕ_p is:

$$\phi_p = \frac{\varepsilon_c}{x} \tag{7}$$

In the formula, ε_c is the peak compressive strain of concrete in the edge of the pressure side; x is the cross -section height of compression zone.
According to literature [44], the calculation formula of ε_c is:

$$\varepsilon_c = \left(700 + 172\sqrt{f_c}\right) \times 10^{-6} \tag{8}$$

where f_c is the axial compressive strength of concrete. Studies [45] have shown that, when compressive strain at the section edge reaches peak strain of concrete, the section height of compression zone remains unchanged. Therefore, x can be defined by calculating the relationship between force and equilibrium in the section limit state (i.e. CP state).
Shear wall with concealed bracings which tends to bending failure belongs to compression member with large eccentricity. In the tension zone, when the reinforcements or steels of boundary elements or embedded columns reach the yield stress, most vertical distribution bars of wall tension zone also reach the yield stress. The stresses of reinforcement near the neutral axis are small, so when calculating, it has no need to consider this part. The tensile region only takes into consideration tensile reinforcements within scope of $h_w - 1.5\,x$ away from tensile edge; the vertical distribution reinforcements in compression zone prone to buckling due to the smaller cross-sectional area, so this part of compressive stress will not be considered either; the longitudinal reinforcements and steels of compressive edge are yielded by compression.
When calculating concrete pressure of shear wall section N_c, the actual compressive stress diagram is substituted with the equivalent rectangular stress diagram, of which compression zone height is 0.8 times the height of the actual compression zone:

$$N = N_c - N_{sw} \tag{9}$$

As symmetrical reinforcement is generally adopted, the equilibrium equation is as follows:

(1) When there are embedded columns or no boundary elements:

$$N_c = 0.8 f_c b_w x$$

$$N_{sw} = f_{yw} b_w \rho_w (h_{wo} - 1.5x)$$

Applying them to the formula (9), we can calculate the height of concrete in the compression zone:

$$x = \frac{N + f_{yw} b_w \rho_w h_{wo}}{1.5 f_{yw} b_w \rho_w + 0.8 f_c b_w} \tag{10}$$

(2) When the compression zone belongs to flange section or side column:

$$N_c = f_c b_f h_f + f_c b_w (0.8x - h_f)$$

$$N_{sw} = f_{yw} b_w \rho_w (h_{wo} - 1.5x)$$

Similarly, taking them into the formula (9), the height of concrete in the compression zone can be calculated:

$$x = \frac{N + f_{yw} b_w \rho_w h_{wo} + f_c h_f (b_w - b_f)}{1.5 f_{yw} b_w \rho_w + 0.8 f_c b_w} \tag{11}$$

Applying the equation (10) or (11) into the equation (7), the cross-section peak curvature ϕ_p can be figured out.

In the formula, N is the vertical force of the shear wall section, N_c is the concrete resultant force in the compression zone, N_{sw} is the tension of vertical distribution reinforcements; f_c is concrete axial compressive strength; f_{cw} is the tensile strength of wall vertical distribution reinforcements; b_w is the shear wall thickness; h_{wo} is the effective height of shear wall section; ρ_w is vertical distribution reinforcement ratio of shear wall; b_f is the width of the side column or flange section; h_f is the length of side column or flange section.

According to literature [46], the plastic hinge length of shear wall is calculated as:

$$l_p = 0.5h_w \tag{12}$$

where l_p is plastic hinge length; h_w is the cross-section height of shear wall.

From literature [47], that plastic displacement angle of shear wall section can be expressed as follows:

$$\theta_p = \beta_2 \phi_p l_p$$

So the shear wall plastic displacement angle under the condition of LS state θ_{LS} is:

$$\theta_{LS} = \theta_p = \beta_2 \phi_p l_p \tag{13}$$

It is worth mentioning that among them β_2 is an undetermined coefficient.

Fitting experimental data of concealed bracing shear walls, Fig.4 indicates the relation graph between shear span ratio and coefficient β_2 under the condition of embedded columns or no boundary elements. It can be seen from the figure that coefficients β_2 are increased with an increase in shear span ratio, and its envelope is fitted for a function:

$$\beta_2(\lambda) = 0.1892\lambda^2 - 0.136\lambda + 4.0773$$

After comparing fitted values with experimental calculated values, the fitting method has guaranteed rate of 94%.

Fig.5 indicates the relation diagram between shear span ratio and coefficient β_2 under the condition of flange section or side columns.

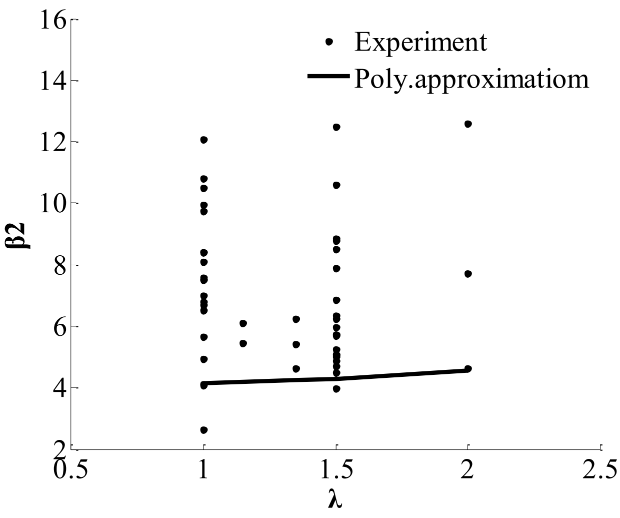

Figure 4. Relationship between coefficient β_2 and shear span ratio λ for embedded columns or no boundary elements.

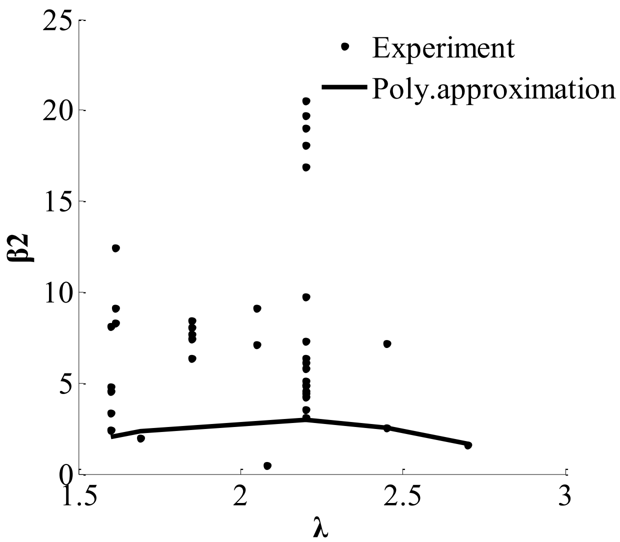

Figure 5. Relationship between coefficient β_2 and shear span ratio λ for flange section or side column.

The coefficients β_2 appear increasing in the first stage, and then decreasing, so it is fitted as a quadratic function:

$$\beta_2(\lambda) = -3.7831\lambda^2 + 15.8815\lambda - 13.6687$$

After comparing fitted values with experimental calculated ones, the fitting method has guaranteed rate of 95%.

3.3 Cross-section plastic displacement angle of CP state

The shear wall component has reached the limit state in the CP state, the criteria for this stage is that the bearing capacity of shear wall critical section decreases to 85% of the maximum bearing capacity, meanwhile, the concrete strain of compression zone reaches the corresponding ultimate compressive strain ε_{cu}.

The limit curvature of the cross-section corresponding to CP state ϕ_u is:

$$\phi_u = \frac{\varepsilon_{cu}}{x} \tag{14}$$

In the formula, ε_{cu} is the limit compressive strain of concrete in the edge of compression side; x is the section height of compression zone.

Limit curvature corresponding to the section height of compression zone can be determined by equation (10) or (11).

When calculating normal section compressive bearing capacity of shear wall with concealed bracings, the stress-strain relationship of compressive concrete is confirmed by the current seismic code in China, i.e.

$$\varepsilon_{cu} = 0.0033 - (f_{cu,k} - 50)\times 10^{-5} \tag{15}$$

where $f_{cu,k}$ is the cube compressive strength of concrete. Consequently, the ultimate compressive strain of concrete adopts 0.0033.

Similar to the LS state, CP state corresponding section plastic displacement angle is:

$$\theta_{CP} = \theta_u = \beta_3 \phi_u l_p \tag{16}$$

where β_3 is an undetermined coefficient; l_p is the length of plastic hinge which is calculated by the equation (12).

According to whether there have boundary elements or not, the relationship between undetermined coefficient and shear span ratio is shown in the following two diagrams. Fig.6 indicates the relationship between coefficient β_3 and shear span ratio under the condition of embedded columns or no boundary elements. It can be seen from the figure that coefficients β_3 are obviously increased by increasing the shear span ratio, and its envelope is fitted for a function as:

$$\beta_3(\lambda) = 0.34\lambda^2 + 0.49\lambda + 2.83$$

After comparing fitted values with experimental calculated values, the fitting method has guaranteed rate of 98%.

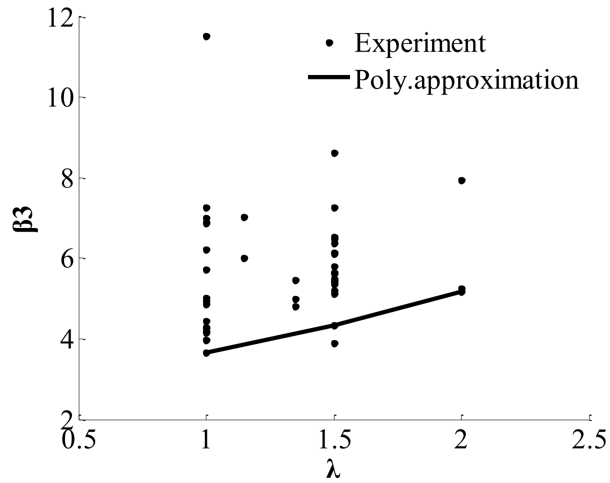

Figure 6. Relationship between coefficient β_3 and shear span ratio λ for embedded columns or no boundary elements.

Fig. 7 indicates the relationship between coefficient β_3 and shear span ratio under the condition of flange section or side columns. The coefficients β_3 appear increasing with the rising of shear span ratio, it is fitted as a function:

$$\beta_3(\lambda) = 7.5882\lambda^2 - 26.2453\lambda + 24.0826$$

After comparing fitted values with experimental calculated values, the fitting method has guaranteed rate of 95%.

4 Performance indexes

For shear wall, the performance level of inelastic state is controlled by the section plastic displacement angle which reflects the degree of the plastic state to a certain extent, namely, the size of its ductility.

To determine the performance indexes for the shear wall with concealed bracings from experimental data, the distribution scope of section plastic displacement angle in the IO performance level is 0.004 ~ 0.014, and the average value is 0.007; similar to IO performance level, the distribution scope of section plastic displacement angle in the LS performance level is 0.006 ~ 0.025, and the average value is 0.014; in the CP performance level, the distribution scope of section plastic displacement angle is 0.009 ~ 0.046, and the average value is 0.028.

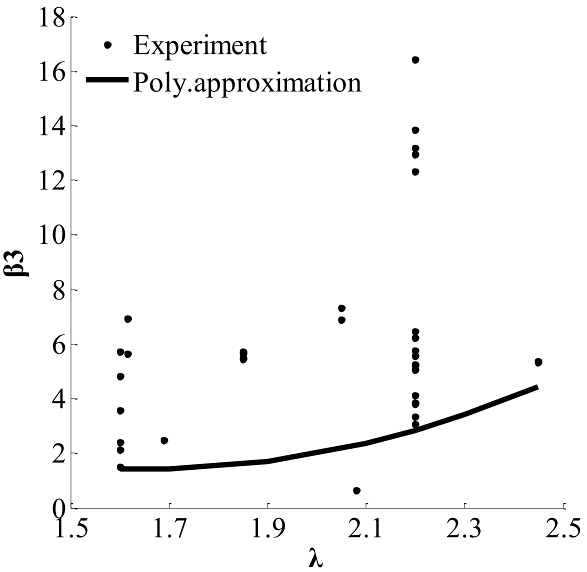

Figure 7. Relationship between coefficient β_3 and shear span ratio λ for flange section or side columns

The comparison of the average test values with Chinese and USA specification is shown in Table 3. As can be seen from the table, under different levels, plastic displacement angles of shear wall with concealed bracings have a large gap with specifications either for China or for the United States, the reasons may be as follows:

In Chinese seismic code, it only has elastic and elastic-plastic story drift limits for the overall structure, and both are applicable to ordinary shear wall. And since the performance indexes of the component are deficient, the values are relatively rough;The intensity grade of materials is not the same in American and Chinese specifications, and the calculation methods of basic parameters are also inconsistent, therefore, it will lead to different performance index limits.

(1) Compared with ordinary shear wall, concealed bracings shear wall has diagonal steel bracings which constitute steel skeleton together with vertical and horizontal reinforcements. Especially the existence of concealed bracings, effectively control the development of cracks, and it is beneficial for the redistribution of internal force. As plastic hinge region of composite shear wall with concealed bracings is large, it also gives full play to energy dissipation capacity for each part of shear wall. So, what can be proved theoretically is that the section plastic displacement angle of composite shear wall is larger than the ordinary shear wall, which is reasonable. At the same time, inelastic displacement and energy dissipation capacity are significantly improved.

(2) Because of different experimental conditions, the data will show a certain degree of discrete. To get more accurate performance indexes a lot of experiments are still needed to be confirmed [48].

From the data in Table 3 it is not difficult to find that test values of plastic displacement angle are about 2 ~ 3 times the corresponding FEMA 356 code values, therefore, we can present a safety reserve value K, to provide certain reliability for shear walls. As plastic deformation ability of the shear wall with concealed bracings is better than ordinary shear wall, we still need to ensure that the displacement angle limits are larger than the ordinary ones.

Table 3. Comparison of shear wall performance indexes in different specifications

Plastic displacement angle	Average test value	Chinese seismic design code	FEMA 356
θ_{IO}	0.007	0.001	0.003
θ_{LS}	0.014	0.004	0.006
θ_{CP}	0.028	0.008	0.009

Referring to the Chinese seismic code, when K = 2.5,

$$\theta_{IO}=0.007/2.5=0.003>0.001,$$

$$\theta_{LS}=0.014/2.5=0.006>0.004,$$

$$\theta_{CP}=0.028/2.5=0.011>0.008\ ,$$

For three performance levels, when taking safety reserve value K into account, displacement angle values not only comply with the above requirements, but are also close to the recommendations in FEMA356, and so the reliability is guaranteed. Therefore, take 0.003, 0.006 and 0.011 as the limit values of section plastic displacement angles for concealed bracings shear wall under the three performance levels.

5 Conclusion

Applying performance-based seismic design method to shear wall with concealed bracing is a new attempt. With reference to American FEMA356 specification, shear wall performance levels are divided into three stages which are in line with the three level design methodology in China seismic code. Then sectional plastic displacement angles have been deduced under different performance levels through the analysis on test data of 89 pieces of shear walls. After that, the computing coefficients related to shear span ratio are fitted out, and have a high reliability. In order to make results more reliable, safety reserve value K is put forward in the process of determining performance indexes for shear wall with concealed bracings. Compared with ordinary shear wall studied by previous scholars, concealed bracing shear wall has better performance of energy consumption, and larger plastic deformation. The application of performance-based approach enables stage design, and imposes it in promoting design and engineering applications for shear wall with concealed bracings.

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