EXPERIMENTAL STUDY ON SEISMIC BEHAVIOR OF HIGH PERFORMANCE CONCRETE SHEAR WALL WITH NEW STRATEGY OF TRANSVERSE CONFINING STIRRUPS

Mingke DENG[1], Xingwen LIANG[2] and Kejia YANG[3]

[1] *Lecturer, School of Civil Engineering, Xi'an University of Architecture & Technology, Xi'an, China*
Email: dengmingke@126.com
[2] *Professor, School of Civil Engineering, Xi'an University of Architecture & Technology, Xi'an, China*
[3] *Lecturer, School of Architecture and Civil Engineering, Wenzhou University, Wenzhou, China*

ABSTRACT:
In order to improve the deformability of high performance concrete shear wall, a new strategy of transverse confining stirrup, which is called piecewise confining stirrups, was presented in this paper. Four specimens of high performance concrete shear wall were designed and the quasi-static test had been carried out according to performance-based seismic design theory. Then, the influence of the axial compression ratio, the amount and range of confinement reinforcement on the ductility, the capacity of energy dissipation and failure behavior was analyzed. It was shown that the confining effect of shear wall sections is improved by the new strategy of transverse confining stirrup. In addition, the amount and range of piecewise confining stirrups determined by the axial compression ratio and displacement ductility demand was demonstrated to be reasonable. The seismic behavior of high performance concrete shear walls was obviously improved and the ductility level of the specimens met the demands of design.

KEYWORDS: high performance concrete, shear wall, ductility, axial compression ratio, piecewise confining stirrups

1. INTRODUCTION

High performance concrete is with the merit of high strength, better fluidity, high durability and impermeability (Cheng 1997; Zhou 2004; Feng 2004) which meet the need of modern engineering structure for large span, high rise, heave load and bad environmental condition. High performance concrete leads an important developing trend in concrete technology. Shear wall is with large lateral stiffness and can decrease lateral displacement of buildings, so it is widely used in modern high rise buildings. The application of high performance concrete shear wall can decrease wall thickness and improve room space, which bring great social and economic benefits. But fragility and poor deformability of high performance concrete shear wall restrict its application on a certain degree. So its seismic performance, especially deformability, needs to be improved. So far, experimental studies on high performance concrete shear wall are not adequate (Cheng *et al*. 1992; Zhuo *et al*. 2001; Li *et al*. 2004; Oh *et al*. 2002;) and most of them adopt ordinary transverse reinforcement strategy, which can not improve the deformability of shear wall significantly. Therefore, based on experimental studies, a new transverse reinforcement strategy that can improve shear wall deformability is proposed in this paper.

2. NEW TRANSVERSE CONFINING REINFORCEMEN STRATEGY

Sectional height of concrete shear wall is large so both ends of the section will yield firstly and reach ultimate state under horizontal load. At the same time, compression strength of most part of the section is not fully made use of and the horizontal bearing capacity and lateral deformability can not be fully exhibited. To improve lateral deformability of shear wall, Chinese relevant code (GB50011-2001; GB50010-2002; JGJ3-2001) require that boundary elements should be arranged on both sides whose range and volume reinforcement characteristic value are also provided.

When the embedded columns are arranged on both sides of the shear wall section as the confining boundary components, the general procedures include placing a close stirrup within the range of the confining length and arranging necessary tie bars to decrease the unsupported length of stirrups and improve the confining effects. If the strain of concrete close to the exterior edge within the confining stirrups reaches ultimate state under lateral load, the stirrups yield and can not confine the other concrete within the confining stirrups effectively before the component reaches ultimate state. Therefore, ordinary transverse reinforcement strategies have limited effects on the lateral deformability of components with large height (e.g. shear walls with large section height). New transverse reinforcement strategy should be developed for this purpose.

Because the shear wall section height is large, several relatively short stirrups may be arranged within the confining range. The short stirrups connect to each other at the longitudinal reinforcements. This is called piecewise confining stirrups. When the concrete within the outmost stirrup reaches the ultimate state, the load can be transformed to concrete within the adjacent stirrup; the rest may be deduced by analogy. This new reinforcement strategy can assure that all concrete within the boundary confining stirrups reaches the ultimate state. Therefore, the lateral deformability of the shear wall will be increased effectively. In addition, since the high strength stirrups have short yield plateau (soft steel) or no yield plateau (hard steel), the strain after yielding is small. Because high strength stirrups can confine the concrete effectively after yielding, it is adopted in the new reinforcement strategy.

To verify the above theories, four high performance concrete shear walls were designed based on different ductility demand, on which quasi-static experiment are performed. The effects of axial compression ratio, confining stirrup quantity and range to shear wall ductility are analyzed to verify the effectiveness of the piecewise confining stirrups.

3. EXPERIMENT RESULT ANALYSIS

3.1. Design and construction of test specimens

Four cantilever high performance shear wall with the concrete grade of C80 were constructed. The cross section is 1000mm×100mm, the wall height is 2000mm and the shear span ratio is 2.1. The specimens are numbered as HPCW-01, HPCW-02、HPCW-03 and HPCW-04. The axial compression ratio of HPCW-01 and HPCW-02 is 0.21; the axial compression ratio of HPCW-03 and HPCW-04 is 0.28; the vertical load is 1004kN. Design ductility demand of HPCW-01 and HPCW-03 is 3 and that of HPCW-02 and HPCW-04 is 4. A concrete loading beam was arranged on the top of the shear wall, and steel plates were embedded in both sides of the loading beam. Bottom beams were arranged under the shear walls. Embedded columns were arranged on both sides of the wall cross sections and longitudinal reinforcements were placed in the embedded columns to simulate the reinforcement of shear walls in actual structure. To improve the confining effects of stirrups to concrete and improve concrete ductility, the following two measures were taken: (1) high strength steel wires with the diameter of 4, 5 and 6mm were placed in the embedded columns, their tensile strength are 836, 713 and 601MPa, respectively; (2) adopt piecewise confining stirrups, i.e., divide the confining range into several independent parts, concrete within each part is confined separately and the confining stirrups are connected with the adjacent ones by longitudinal reinforcements, as is shown in figure 1. The strength of reinforcements and concrete were determined before the experiment, see table 1.

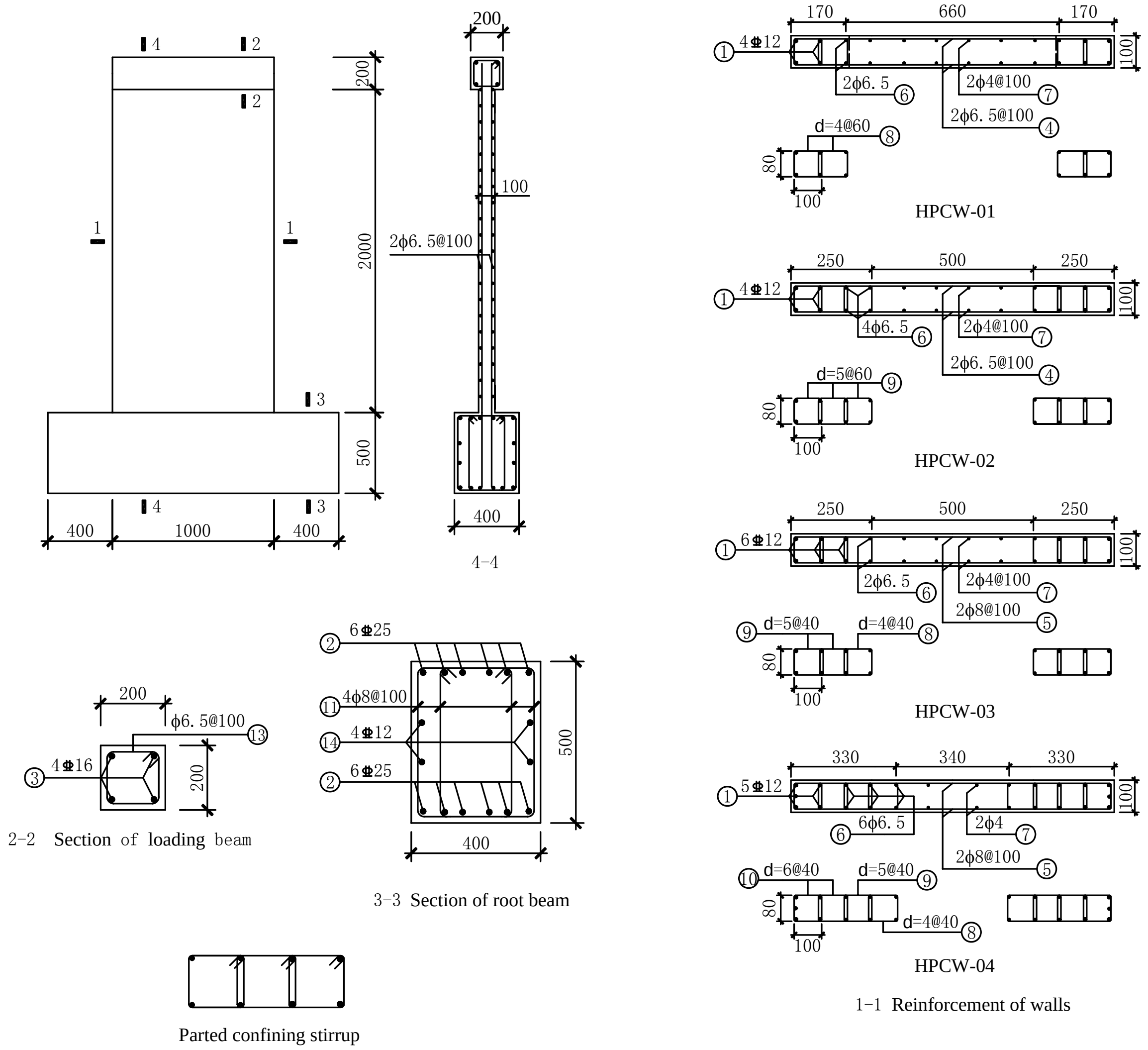


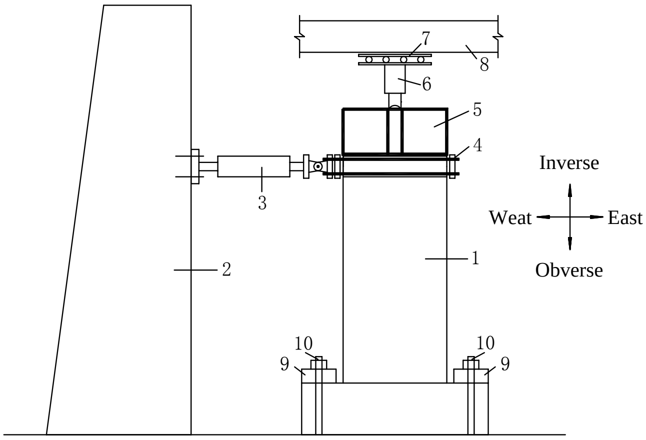
Fig. 1 Dimensions of walls and arrangement of reinforcement

Table 1 Strength of the reinforcement and concrete

Bar	Bar type	$f_y/\mathrm{N\cdot mm^{-2}}$	$f_u/\mathrm{N\cdot mm^{2}}$	Specimen number	f_{cu} (MPa)
HRB400	Φ**25**	460.4	639.7	1	61.43
	Φ**12**	433.3	636.6	2	73.56
Hard-drawn	d=6	—	601	3	75.32
	d=5	—	713	4	86.02
	d=4	—	836	5	64.17
HPB235	ϕ**6.5**	361.6	506.3	6	77.33

3.2. Test Instruments and Contents

The low cyclic reversed loading method is adopted in the experiment, and the loading instruments are as shown in figure 2. Vertical loads were applied firstly in the experiment which applied central point loading. The loads were transformed to the loading beam uniformly through stiff pillow beam. The vertical loads were applied in 2 or 3 steps which remained constant during the experiment. Then the horizontal loads were applied, which were controlled by load and displacement. The yielding of specimens were controlled by load. When the wall was close to crack or yielding, the loading step difference was decreased to search the crack load and yielding load. After yielding, the loading was controlled by displacement and displacements applied were multiples of the yielding displacement. Each load grade cycled three times and the loading would not stop until the shear wall failed or the load decreased to less than 85% of the maximum load.



1 Specimens
2 Reaction wall
3 Actuator
4 Connecting bar
5 Pad beam
6 Load cell
7 Sliding bearing
8 Reaction beam
9 Press beam
10 Bolt

Figure 2 Experimental set-up

3.3. Failure Analyses

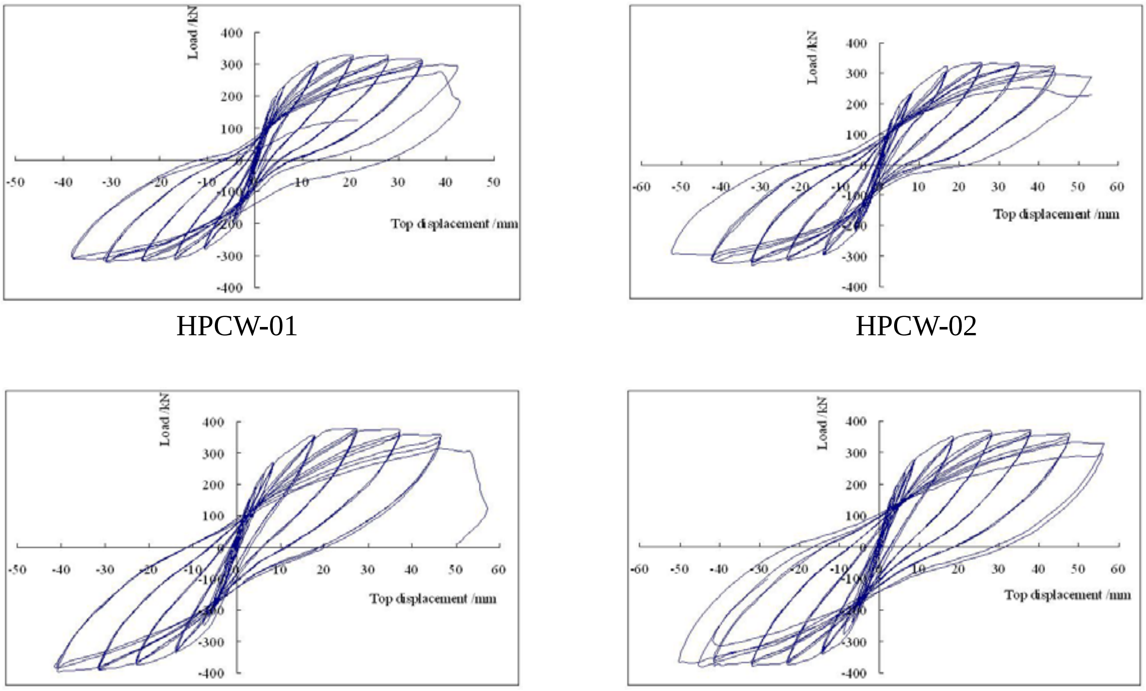
Common failure features and rules of the four high performance concrete shear walls are: the cracks formed at the lower part of the wall before yielding and most of them were horizontal flexural cracks; after yielding, especially after $2\Delta_y$, many shear-flexural cracks formed at the lower part of the wall. When the load reached about 4~5Δ_y, 2~3 pieces of the shear-flexural cracks extend significantly and formed critical diagonal cracks. The shear wall failure was caused by crushing of concrete in the compression area or break of tensile reinforcements in the tensile area. Therefore, the failure was bending failure.

The range and quantities of confining stirrups in HPCW-01 and HPCW-03 were designed corresponding to the ductility demand 3 and that of the other two walls were designed corresponding to the ductility demand 4. The experimental results show that failure of HPCW-01 and HPCW-03 was caused by crushing of concrete in the compression area after the break of tensile reinforcements in the tensile area. Failure of the other two walls was caused by the break of tensile reinforcements in the tensile area. The concrete in the core of compression area was not crushed. As can be concluded that range and quantity of confining stirrups determined by displacement ductility can not only improve deformability but also change the failure mode of the components. Longitudinal reinforcements in the experiment are HRB400 with the measured mean yielding strength of 433.3MPa and ultimate strength of 636.5MPa. Break of tensile reinforcements show that well confined compression concrete can have large deformability and the high strength piecewise confining stirrups confined the core concrete effectively.

4. DEFORMATION AND ENERGY DISSIPATION ANALYSIS OF HIGH PERFORMANCE CONCRETE SHEAR WALLS

4.1. Load-displacement Hysteresis Characteristic

Load-displacement hysteresis curves of the 4 shear walls are shown in figure 3. Comparison analyses show the following features and rules: the shear walls are in elastic stage before cracking and the loading and unloading curves overlap as a straight line; between crack and yield, the area within hysteresis curves is small, the loops are lathy and the stiffness decrease, residual deformation and energy dissipation of shear walls are small; after yielding, the hysteresis curve start to incline toward the displacement axis, the loop area and energy dissipation increase; under the same displacement, the first cycle is with larger stiffness than the other two cycles; the hysteresis curves are not symmetrical. They deviate toward the positive direction because of initial loading direction and the eccentric moment due to vertical load. The difference between displacement of actuator and that of the shear wall also increases this deviation; the hysteresis curves are all plump which indicates that the shear walls are with large energy dissipating capacity; the hysteresis curves' area increase even after the ultimate state when their bearing capacity decrease on certain degree, which shows that the shear walls are with large plastic deformability. At this time, the energy dissipation is due to opening and close of the crack. The area of hysteresis curves of HPCW-02 and HPCW-04 are larger than that of HPCW-01 and HPCW-03, which shows that the energy dissipating capacity of the shear wall increases after taking some effective measures.



HPCW-01 HPCW-02

HPCW-03 HPCW-04

Figure 3 Hysterisis loops of different specimens

4.2. Skeleton Curves

According to the load-displacement hysteresis curves, the skeleton curves of the 4 shear walls are drawn and compared corresponding to different axial compression ratios, see figure 4. As can be seen that the post yield deformability of shear walls increase with the increase of quantity and range of the confining stirrups provide that the axial compression ratio are the same.

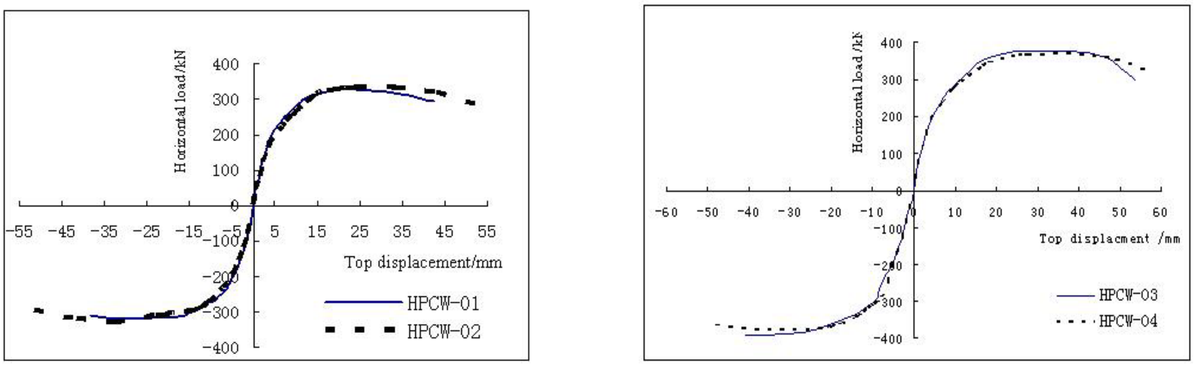


Fig. 4 Skeleton curves

4.3. Deformation Capacity Analysis

The cracking load was determined by formation of obvious small cracks at the bottom of the wall. The peak load of the skeleton curves is taken as the ultimate load corresponding to the peak displacement. There were no significant turning points during yielding and the yielding point was determined by “general yielding moment method”. Shear deformation played an important role in the experiment. Many diagonal shear cracks formed during the experiment, but the final failure modes were bending failure. The ultimate displacement was determined when the bearing capacity in the skeleton curve decreased to 85% of the ultimate load. The displacement ductility of the shear walls were determined by the ratios of ultimate displacements and yielding displacements. The characteristic point and ductility of the shear wall are shown in table 2.

Table 2 Comparisons of characteristic point and ductility

Specimen number	Crack		Yield		Ultimate			Ductility	Ratio
	Load P_{cr} /kN	Displacement Δ_{cr} /mm	Load P_y /kN	Displacement Δ_y /mm	Load P_u /kN	Peak Δ_0 /mm	Ultimate Δ_u /mm	$\mu=\frac{\Delta_u}{\Delta_y}$	$\theta=\frac{\Delta_u}{H}$
HPCW-01	160	3.1	264	8.5	326.3	20.42	42.39	4.99	1/49
HPCW-02	160	3.2	255	9	332.6	24.55	52.08	5.79	1/40
HPCW-03	200	4.3	277	8.8	379.3	27.26	51.4	5.84	1/41
HPCW-04	160	3.2	270	9.1	370.3	37.93	56.22	6.18	1/37

As can be seen from table 2, yielding displacement of the 4 shear walls are very close. the larger axial compression ratio is, the larger cracking load will be; when the confining effect of the stirrups are improved, the peak displacement corresponding to ultimate load and the ultimate displacement will also increase. Provide that the axial compression ratios are the same, peak displacement of HPCW-02 is 20.2% larger than that of HPCW-01 and the ultimate displacement of HPCW-02 is 22.9% larger than that of HPCW-01; compared with HPCW-03, the peak displacement and ultimate displacement of HPCW-04 increase by 39.1% and 9.4%, respectively. It can be conclude that piece wise confining stirrups with larger confining range can still improve the deformability of high performance shear walls when the axial compression ratio is large.

As can be seen from figure 5 and table 2, the bearing capacity of the 4 shear walls keep increasing after yielding and it reached the peak value when the lateral displacement reached 3 times the yielding displacement; the bearing capacity decrease little before the lateral displacement reached 5 times the yielding displacement; the ultimate deformability of the shear walls increase with the increase of confining stirrups. If the axial compression ratios are constant, the displacement ductility of HPCW-02 is 16% larger than that of HPCW-01, and the displacement ductility of HPCW-04 is 5.8% larger than that of HPCW-03, which indicate that piece wise confining stirrups and performance based deformability design can improve the deformation capacity of shear wall significantly and assure that high performance shear wall have adequate ductility.

5. CONCLUSIONS

From the experiment and analysis on the 4 high performance concrete shear wall, it can be concluded that:

(1) Under low cyclic reversed load, the failure of high performance concrete with piece wise confining stirrups is caused by core concrete crush after yielding of tensile reinforcements or by break of tensile reinforcements and crush of part of core concrete. The compression-bending bearing capacity is fully exhibited and the deformability is good.

(2) Axial compression ratio and the range and quantity of confining stirrups affect deformability of shear walls significantly. When the axial compression ratio increases, adequate ductility can be achieved by increasing the range and quantity of shear wall boundary confining stirrups.

(3) According to the displacement ductility demand and axial compression ratio requirements, the high performance concrete shear wall can obtain adequate deformability if range and quantity of confining stirrups are determined by performance-based design method. The experiment results show that shear walls designed according to ductility demand 3 and 4 can actually obtain displacement ductility of 5.42 and 5.99, respectively.

(4) The actual axial compression ratio of the two specimens is 0.28 which is nearly 0.5 if converted into design axial compression ratio (load and material strength adopt design value). The results show that shear walls with piece wise confining stirrups can still obtain adequate ductility, which verifies effectiveness of piece wise confining stirrups to core concrete.

(5) Energy dissipating capacity of shear walls closely related to ranged and quantity of boundary confining stirrups. The shear wall energy dissipating capacity can be significantly improved with the increase of range and quantity of confining stirrups.

7. ACKNOWLEDGEMENT

This research was supported by the China National Natural Science Foundation (Grant No. 50678146) and the Science and Technology Foundation of Xi’an University of architecture and technology (Grant No. RC 0731).

REFERENCES

CHENG Zhao-yuan, ZHU Jin-quan, WU Pei-gang. (1992). High-strength concrete and application[M].Beijing: Tsinghua University press. (In Chinese)
CHENG Zhao-yuan. (1997). Devolopment and utilization of high-strength and high-performance concrete[J]. China *Journal of Civil Engineering*, 30(5): 3~11.(In Chinese)
Code for seismic design of building structures (50011-2001)[S].Beijing: China press of architecture industrial. (In Chinese)
Code for Concrete structure design (GB50010-2002)[S].Beijing: China press of architecture industrial. (In Chinese)
FENG Nai-qian. (2004). High-performance concrete structures[M].Beijing: China machine press. (In Chinese)
LI Hong-nan, LI Bing. (2004). Experimental study on seismic restoring performance of reinforced concrete

shear walls[J]. *Jounal of Building Structures*, 25(5): 35~42. (In Chinese)

OH Young-Hun, HAN Sang Whan, LEE Li-Hyung. (2002). Effect of boundary element details on the seismic deformation capacity of structural walls. *Earthquake Engineering and Structural Dynamics*, 31(8):1583~1602.

Technical specification for concrete structures of tall building (JGJ3-2002)[S].Beijing: China press of architecture industrial. (In Chinese)

ZHUO Xiao-bao, DAI Zi-qiang, LI Yan-bo. (2001). Research on improving the seismic behavior of high strength concrete shear walls[J]. *Industrial Construction*, 31(6):37~39. (In Chinese)

ZHOU Lu. (2004). A comment of the development of high-performance concrete[J]. *Building Structures*, 34(6):65-72. (In Chinese)