COMPDYN 2013
4th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
X.L. Dang, Y. Zhou, X.L. Lu
Kos Island, Greece, 12–14 June 2013

SEISMIC PERFORMANCE OF PRE-STRESSED SHEAR WALLS WITH BOTTOM HORIZONTAL SLITS AND BUCKLING RESTRAINED REINFORCEMENT

Xiangliang Dang[1], Ying Zhou[2], Xilin Lu[2]

[1]College of Civil Engineering, Tongji University,
Shanghai 200092, China
11dangxiangliang@tongji.edu.cn

[2]State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University,
Shanghai 200092, China
yingzhou@tongji.edu.cn
lxlst@tongji.edu.cn

Keywords: Pre-stressed shear walls, bottom horizontal slits, buckling restrained reinforcement, seismic performance, cyclic loading.

Abstract. *The research on seismic behavior of rocking structures with bottom horizontal slits got increasingly attention in recent years. The rocking structures could concentrate the deformation at the bottom slits and use the unbounded pre-stressed tendon to provide self-centering ability. Thus the residual deformation is small and the main structure is protected. This paper researches on the seismic behavior of a new-type pre-stressed shear wall with buckling restrained reinforcement. ABAQUS models are built to study the performance influence of the bottom slits length, slits height, and the number of buckling restrained reinforcement under quasi-static reversed cyclic loading conditions. The comparison is made between the behavior of the new-type walls and the traditional rocking structures. All these walls display a characteristic "flag-shape" hysteretic response. And the walls with buckling restrained reinforcement exhibit higher energy-dissipating ability than the traditional rocking walls do and also higher in lateral capacity. The results indicate that the new-type walls exhibit excellent self-centering property, energy-dissipating ability and the ability of protecting the main structure from being damaged.*

1 INTRODUCTION

Pre-stressed shear walls gain their lateral strength and desirable seismic properties through the utilization of vertical unbounded post-tensioning. In-plane cyclic loading of a pre-stressed shear wall results in a horizontal crack forming at the wall-foundation interface. This leads to rocking behavior which means large drift capacity and reduction of the wall damage, with the wall returning to its original vertical alignment, known as the self-centering ability, provided that sufficient pre-stress remains in the tendons at the end of loading. Existing research on the cyclic and dynamic response of pre-stressed shear walls has demonstrated these characteristics [1,2,3].

The wall toes usually suffer drastic damage after the earthquake as undergoing highest moment and largest strain in the structure. For this reason, this paper replaces wall toes [4] of the pre-stressed shear wall with the energy dissipaters.

Energy dissipaters are frequently used in the pre-stressed shear wall systems to dissipate the seismic energy and to protect the wall from being damaged. In this paper, the buckling restrained reinforcement (BRR) is imported to act as the energy dissipater. The idea of the buckling restrained reinforcement comes from the widely use of buckling restrained brace, known as BRB, which can restrain almost the same compressive loading as well as tension loading without buckling. Results from an experiment program [5] showed that BRBs exhibit ductile, stable and repeatable hysteretic behavior and are suitable for dissipating seismic energy.

In this new type wall, rectangular slits are set at the wall toes and the BRRs are placed vertically inside the slits. There is a horizontal crack at the wall-foundation interface and pre-stressed tendons are used to provide self-centering ability. The sketch of the pre-stressed shear walls with bottom horizontal slits and BRRs is shown in Figure 1.

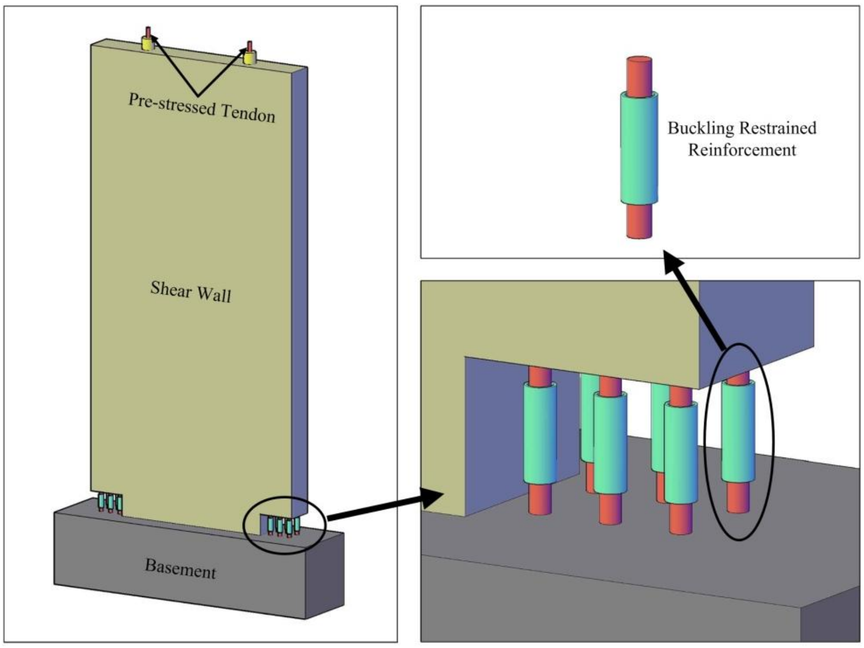


Figure 1: Sketch of the pre-stressed shear wall with bottom slits and BRRs

2 FINITE ELEMENT MODELING

2.1 Modeling method

The finite element software ABAQUS is employed here to investigate the cyclic loading behavior of the new type walls. The concrete is modeled using solid element and meshed as C3D8R while the reinforcement is modeled using truss element. Then the reinforcement mesh is embedded in the whole model to act together with the concrete material. The BRR element applies truss element as well, and end nodes of BRR are bonded to the concrete nodes.

Modeling of the horizontal joint during wall rocking is essential for pre-stressed shear wall systems. A specific contact property is used between the wall base and foundation. In the horizontal direction, it is assumed that no slip would occur between two points once in contact [6], and “hard contact” is adopted in the vertical direction.

This paper uses nonlinear spring element in the ABAQUS to simulate the unbounded post-tensioning tendon. The spring element is set by the means of spring stiffness, K, which is calculated as follow equation:

$$K = \frac{F}{S} = \frac{\sigma A}{\varepsilon l} = \frac{EA}{l} \tag{1}$$

Where l=length of the pre-stress tendon; E=modulus of elasticity; A=area of the pre-stress tendon; F= force in the pre-stress tendon; S= deformation in the pre-stress tendon.

Then the force-displacement curve of the unbounded post-tensioning tendon is obtained by knowing the yield stress and modulus of elasticity, shown in Figure 2:

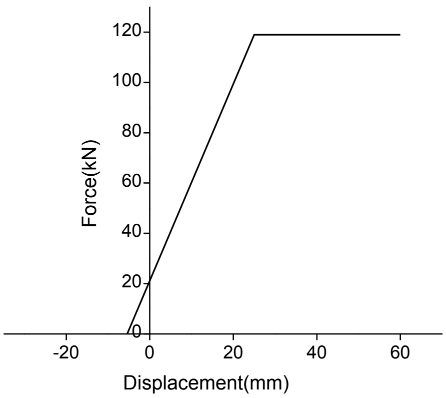


Figure 2: Displacement-force curve of a post-tensioning tendon

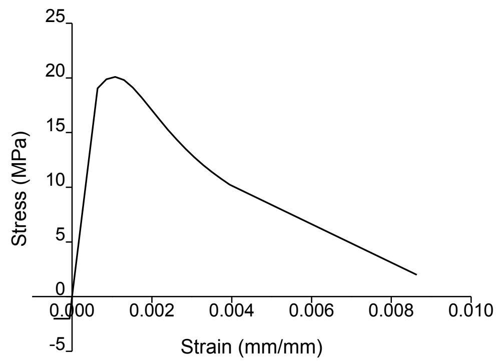


Figure 3: Uniaxial stress-strain relationship of concrete

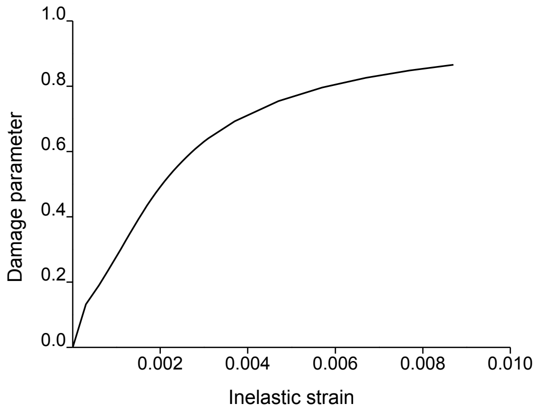
2.2 Material properties

The “concrete damaged plasticity model” is used to predict plastic concrete bebavior for axial tension or compression. Figure 3 shows the uniaxial stress-strain relationship of the concrete used in this paper with a compressive strength of 20.1MPa and tensile strength of

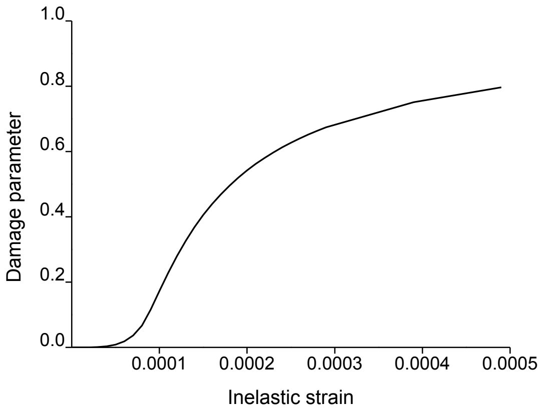
2.01MPa. The tensile strength is capped at the maximum value and no strain softening is permitted to prevent convergence issues [2].

Damage parameters should be defined in the “concrete damaged plasticity model”, and these parameters are obtained according to “Code for design of concrete structures” [7] in China. The relationship of inelastic strain and damage parameters for compression and tension of concrete is shown in Figure 4. The damage parameter values range from 0 to 1, and larger value of parameter means more damage in concrete [8].

The steel constitutive relationship applied two-line relationship including the longitudinal steel bars and the distribution bars, with the yield stress of 335MPa. The yield stress used in the BRR element is 225MPa, and the material used in BRRs has long yield plateau which means perfect energy dissipating ability.



(a) Compression



(b) Tension

Figure 4: Relationship of concrete inelastic strain and damage parameter

2.3 Model details

Eight finite element models in ABAQUS software are built to study the behavior of the walls with bottom horizontal slits and buckling restrained reinforcement. Slits length, slits height and quantity of BRRs are parameters studied in this paper. All of the walls undergo at most 3% drift, which is 96mm, in the analysis. In these models, RW1-0 is the wall without any slits or BRRs. Sectional reinforcement details are shown in Figure 5.

Model number	Slits length/mm	Slits height/mm	Quantity of BRRs
RW1-0	0	0	0
PW1-1	200	80	6
PW1-2	250	80	6
PW1-3	300	80	6
PW2-1	200	40	6
PW2-2	200	120	6
PW3-1	200	80	4
PW3-2	200	80	8

Table 1: Parameters of models

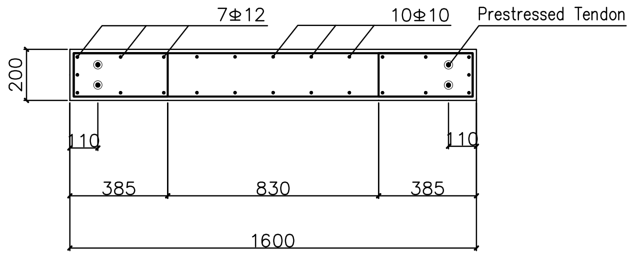


Figure 5: Reinforcement details of models

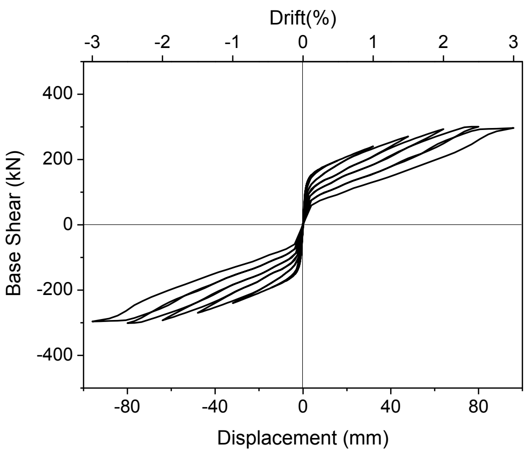
3 ANALYSIS RESULTS

Force-displacement curves under cyclic loading are obtained from the finite element analysis and displayed below. Differences could be found in these figures as the parameter changes.

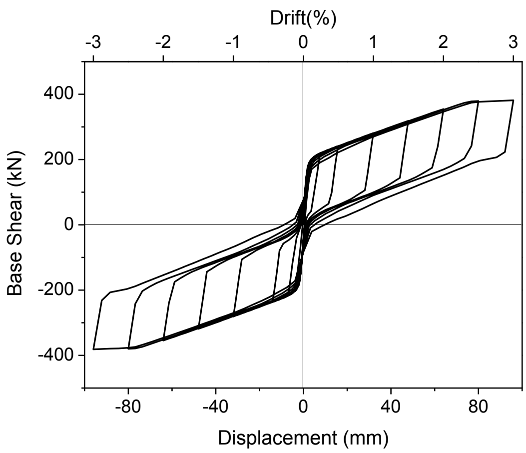
3.1 Slits length

As can be seen from these force-displacement curves, all these walls display a characteristic "flag-shape" [9] hysteresis response, and the lateral capacity of the wall grows slowly when the slits length decrease except RW1-0 which has no slits or BRRs. It is because that the absence of the wall toe may reduce the resisting moment provided from wall base. The larger slits length is, the lower lateral capacity becomes. However, the lateral capacity of the rocking wall is lowest because there are no BRRs to provide extra tensile force at the wall toe.

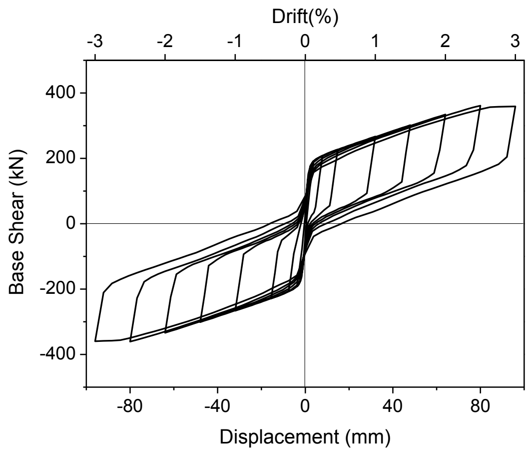
There is obvious difference in the residual drift as the slits length changes although envelop area of the curves remains almost the same. Larger slits length results in more residual drift, which could be explained by knowing that more plastic deformation occurs in the wall base under the vertical loading when the slits length increases.



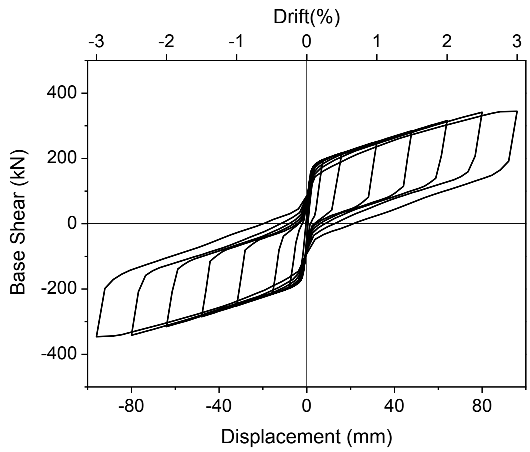
(a) RW1-0



(b) PW1-1



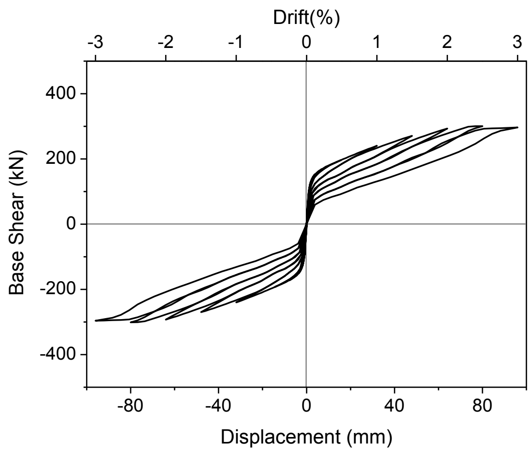
(c) PW1-2



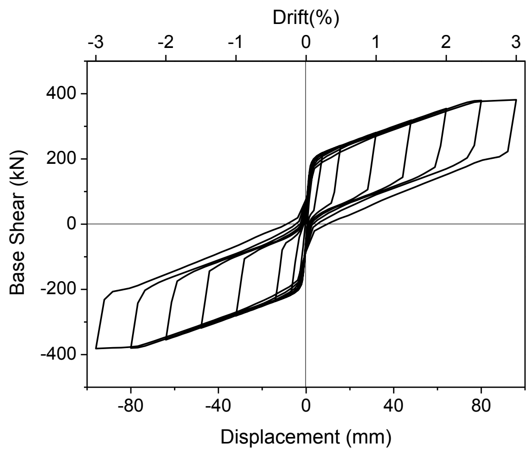
(d) PW1-3

Figure 6: Force-displacement relationship under different slits length

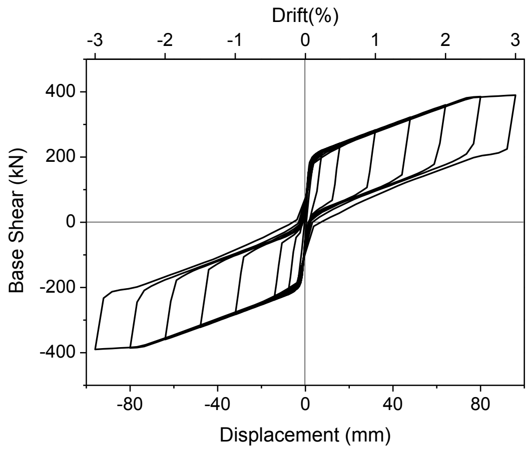
3.2 Slits height



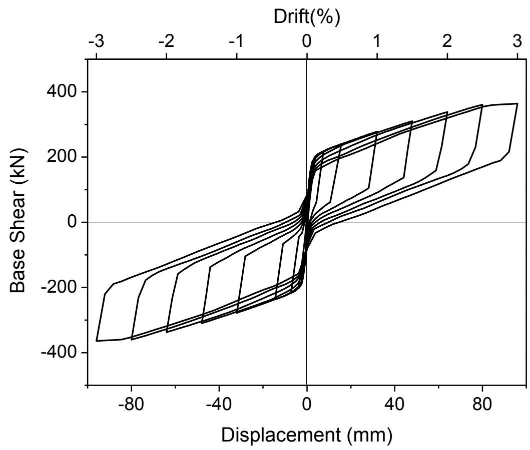
(a) RW1-0



(b) PW1-1



(c) PW2-1



(d) PW2-2

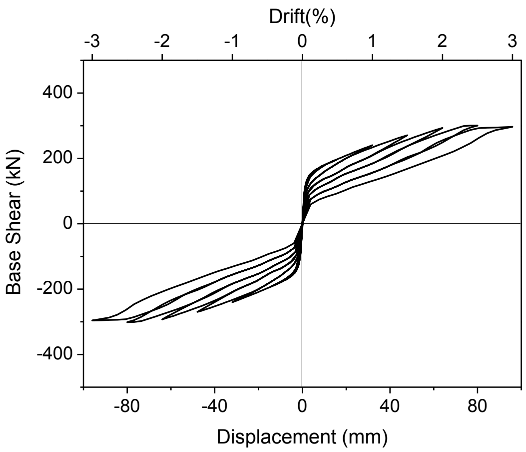
Figure 7: Force-displacement relationship under different slits height

There is no obvious difference of lateral capacity between the curves in Figure 7 when the slits height increases except that RW1-0 exhibits a little lower lateral capacity because of the absence of the wall toe. However, the residual drift become larger as the slits height grows. The reason lies that larger slits height results in more damage in the wall concrete, which causes larger residual drift in the hysteresis curves.

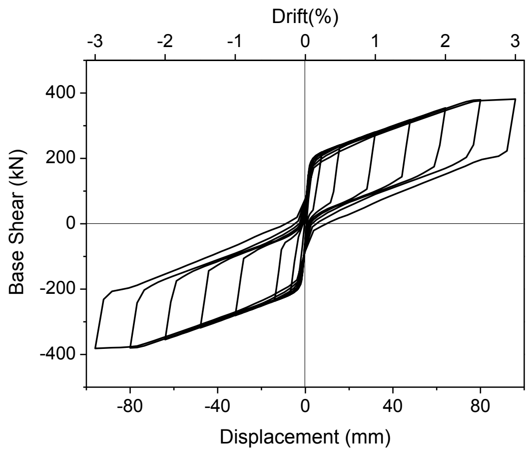
3.3 Quantity of BRRs

As expected beforehand, large quantity of BRRs leads to large envelope area of curves as the BRRs are main energy dissipation members in the pre-stressed shear wall systems. And high lateral capacity is benefited from BRRs because of the extra tensile force that mentioned in section 3.1.

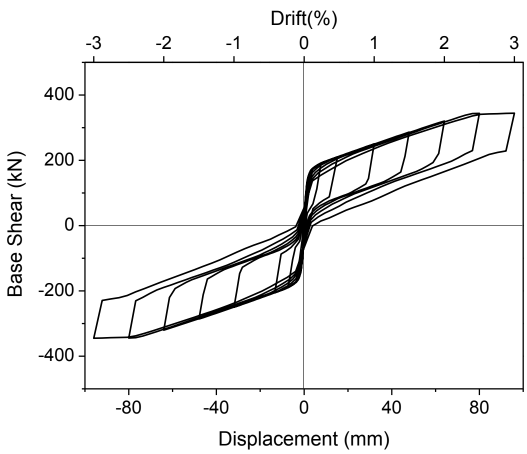
However, use of BRRs not only results in better energy dissipation ability but also leads to larger residual drift. So the quantity of BRRs should depend on the design object of structural system.



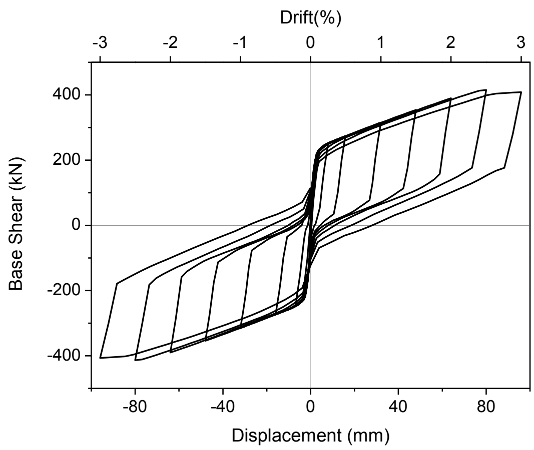
(a) RW1-0



(b) PW1-1



(c) PW3-1



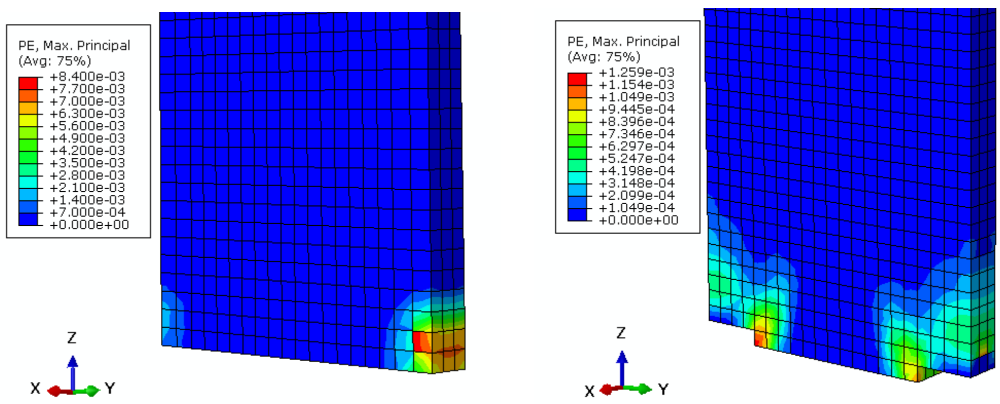
(d) PW3-2

Figure 8: Force-displacement relationship under different quantity of BRRs

3.4 Strain in the wall toe

Two strain contours of the concrete in the walls are displayed here to ensure the contribution made from the BRRs. The wall RW1-0 and PW1-3 are chosen to represent the walls with and without slits. And the figures display the strain state at the drift of 1.5% which is 48mm.

As can be seen from the figures, the maximum plastic strain of concrete in RW1-0 is larger than that in PW1-3, which means less damage observed in the concrete of wall with bottom horizontal slits. The reason is that utilization of BRRs in the wall toe dissipate the seismic energy inputted to the wall system, thus protect the concrete material from being damage severely.



(a) RW1-0 (b) PW1-3

Figure 9: Plastic strain contour of the concrete

4 CONCLUSIONS

- Pre-stressed shear wall with bottom horizontal slits and buckling restrained reinforcements (BRRs) shows a “flag-shape” hysteretic response, which means good self-centering ability is achieved for this new type wall.
- The increase in slits length, slits height and quantity of BRRs results in the growth of residual drift for the wall under cyclic loading.
- The envelop area of the hysteresis curves is largely influenced by the quantity of BRRs. More BRRs provide better energy dissipating ability as well as increase in the lateral capacity.
- By using bottom horizontal slits and BRRs in the wall toe, plastic strains of the concrete are largely reduced and severe damage of the wall is avoided.

REFERENCES

[1]Y.C. Kurama, *Seismic analysis, behavior, and design of unbounded post-tensioned precast concrete walls*. Lehigh University, May, 1997.

[2]R.S. Henry, *Self-centering precast concrete walls for buildings in regions with low to high seismicity*. University of Auckland, June, 2011.

[3]Y. Zhou, X.L. Lu, State-of-the-art on rocking and self-centering structures. *Journal of Building Structures*, **32(9)**, 1-10,2011. (in Chinese)

[4]X.L. Lu, Y. Chen, Y.J. Mao, New concept of structural seismic design: earthquake resilient structures. *Journal of Tongji University(Natural Science)*, **39(7)**, 941-948, 2011. (in Chinese)

[5]C. Black, N. Makris, A. Ian, Component testing, seismic evaluation and characterization of buckling-restrained braces. *Journal of Structural Engineering*, **130(6)**, 880-894, 2004.

[6]G.D. Wight, J.M. Ingham, Tendon stress in unbounded posttensioned masonry walls at nominal in-plane strength. *Journal of Structural Engineering*,**134(6)**, 938-946, 2008.

[7]Ministry of Construction of the People's Republic of China, *Code for Design of Concrete Structures(GB 50010-2010)*. China Architecture & Building Press. Beijing, 2010. (in Chinese)

[8]Hibbitt, Karlsson & Sorensen,INC, *ABAQUS/Standard user's manual*. USA, 2000.

[9]B. Erkmen, A. Schultz, Self-centering behaviour of unbounded, post-tensioned precast concrete shear walls, *Journal of Earthquake Engineering*, **13(7)**, 1047-1064, 2009.