EXPERIMENTAL RESEARCH ON SEISMIC BEHAVIOR
OF PRESTRESSED BRICK MASONRY BUILDINGS

Luo Wankang[1], Xiang Hui[2], and Li Xijun[3]

ABSTRACT

By testing two 1:2 prestressed and non-prestressed brick masonry building models with tie beams and tie columns under horizontal low-cycle loads, the appearance and development of cracks, stiffness, ductility, energy dissipation of the buildings were studied. Analysis of the test results indicates that prestressing on brick masonry not only can increases the anti-cracking ability to some extent, but also improves evidently the behavior of deformation and ductility. The results of this study can provide important theoretical and experimental foundation for application of the pretressed brick masonry buildings in seismic zones.

Key Words: Prestressed; low-cycle load; ductility; energy dissipation

[1]Professor, Civil Engineering Dep. Chongqing JianZhu University, Chongqing, 400045, China. E-mail: jgong@cqjzu.edu.cn
[2]Student, Civil Engineering Dep. Chongqing JianZhu University, Chongqing, 400045, China. E-mail: jgong@cqjzu.edu.cn
[3]Student, Civil Engineering Dep. Chongqing JianZhu University, Chongqing, 400045, China. E-mail: jgong@cqjzu.edu.cn

INTRODUCTION

In order to research the seismic behavior of the prestressed brick masonry buildings, another two three-story-double-room brick masonry building models under horizontal low-cycle loads were tested based to extend the authors' previous work. Same as the experiments on the single brick walls (Li 2000) the steel bars were installed in the tie columns and then pretressed, so the brick panels was prestressed through the elastic-groundsill-beam-effects exerted by the ring beams. The aim was to comprehensively promote seismic behave of the prestressed brick masonry buildings. Additionally, the bend influence resulted from the increase of stories and heights shouldn't be ignored. The experiments will provide worthy inference resource for engineering application of the prestressed brick masonry buildings.

DETAILS OF THE EXPERIMENT

Model Specimens

Figure 1 shows the prestressed brick masonry building model, named PBM, and the non-prestressed brick masonry building model, named BM, respectively. The former was put apart a slot of 30mm thick in the knots of the tie beams and the structural concrete columns firstly. After the tension and anchorage of the steel bars, the slot was filled with concrete of intensity C30. Then the stress force should be transmitted to the brick walls. The practical measured intensities of the models' materials are shown in Table 1.

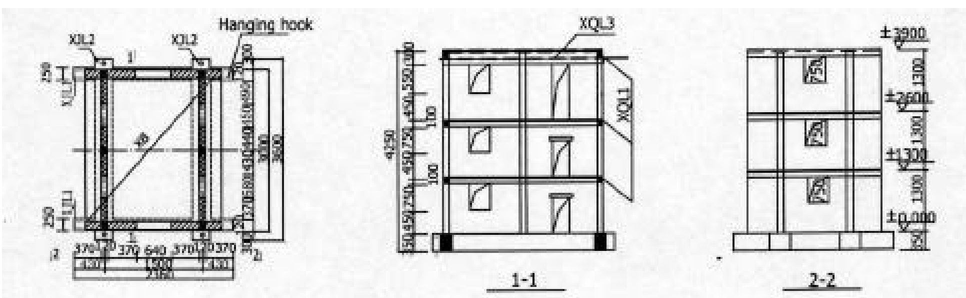


Figure 1. The plan, elevation, and section of the models

Table 1. The practical measured intensities of the models' materials

Material	Brick (MU)	Mortar (M)		Concrete $f_{cu,m}$			Steels f_y		
		BM	PBM	Basement beam	BM	PBM	4	8	^{L}12
Intensity (N/mm^2)	12.2	5.12	4.90	29.9	23.6	18.3	480	418	442

LOADING INSTRUMENTS AND LOADING SCHEME

The loading instruments used in the test can are shown in Figure 2.

Vertical loading. The vertical loads were exerted with weights. The weights of the first and the second floor were both 1.26 ton and that of the third floor was 4.41 ton. Although only three stories had been made in the model because of the limitation of lifting capacity of the lab, the walls of the fourth floor and roof loads had been counted within the third floor. Through computing and adjusting, the location of the resultant force of reversed triangle seismic action approaches the gravity center of the ring beam in the third floor, so it is regarded as the point of horizontal loading.

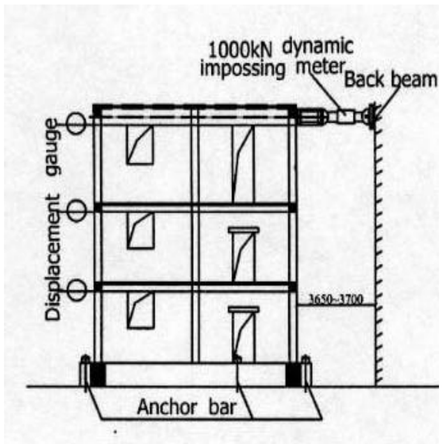


Figure 2. Loading instrument drawing

Prestessing through post-tension method. Tension controlled stress was taken as $_{con}$=0.6f_{pyk}=265.2Mpa. After the anchorage of the prestessed steels, the slot was filled with concrete of intensity C30. When PBM reached the required intensity, the horizontal loads were loaded.

Horizontal loading. It was controlled with load before cracking and with displacement after cracking, circulating three times each step of loading.

MEASUREMENT METHOD

The following quantities were measured with the strain pieces and displacement meters shown in Figure 3 and Figure 4:

(1)The change of strains of the steels and brick walls measured with stain pieces to determine the initial values and the loss values of the prestress;

(2) The distribution of the compressive stress caused by the elastic-groundsill-beam-effect

of the ring beams after prestressed;

(3) V-   hysteretic curve;

(4) The stress change of measured points after loaded;

(5) The appearance, development of the cracks and the destruction process of the models.

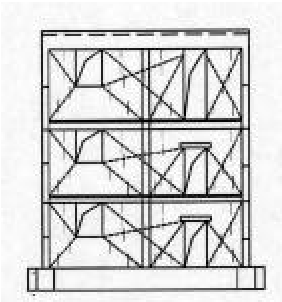


Figure 3. Stain pieces drawing of horizontal walls

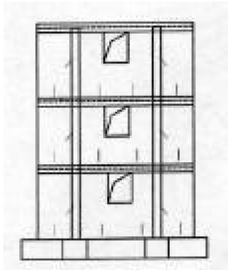


Figure 4. Stain pieces drawing of vertical walls

ANALYSIS OF THE RESULTS

Primary analysis of the experiment results

The experimental results are shown in Table 2.

Table 2. Primary analysis of the experimental results

Model	State of cracking		State of Ultimation		Vertical compression	Average shear intensity	Deforming pattern		V_{cr}/V_u	V_{cr}/V_u	V_{cr}/V_u
	V_{cr} (KN)	$_{cr}$ (mm)	V_u (KN)	$_u$ (mm)	$_o$, $_{op}$ (N/mm^2)	V_{cr}/A (N/mm^2)	Pre-cracking	Post-cracking			
BM	140	11.07	180	46.19	$_o$=0.360	0.194	Shearing Type	Bend-Shearing Type	0.78	1.43	1.31
PBM	160	10.12	235	55.41	$_o$=0.360 $_{op}$=0.307	0.222			0.68		

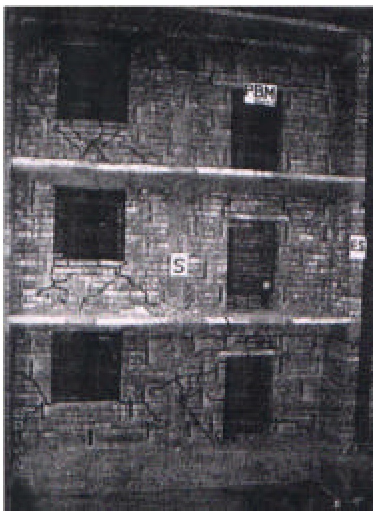
The Process, state, and mechanism of the damage

For convenience, the models are described by four sides, east, south, west, and north, among which the side nearing resistance wall is determined to be the east side. The states of cracking and destruction of the models, shown in figure 5, are presented respectively as follows:

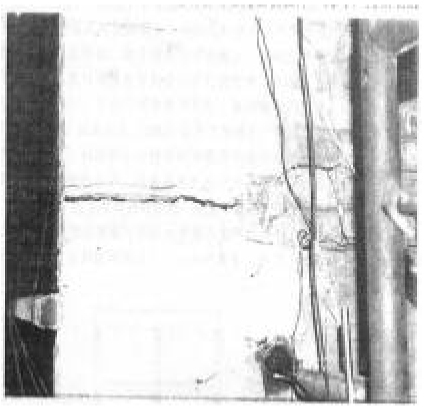
BM. As shown in Figure 5(a), when horizontal load reached the third circulation of 140KN, the whole model had been crossed by ladder cracks. In the meantime, the cracks of middle columns of the north wall of the first floor had been crossed, too. Until then the brick walls had cracked completely. Consequently, 140KN may be taken as its cracking load. With the increase of the value of *V*, the cracks developed comprehensively. Until 180KN, the horizontal crack of the longitudinal walls of the first floor had developed towards to 4-5mm width and continuously stretched towards windows of the transverse walls, and the cohesion of the masonry mortar under the ring beams had lost thoroughly. Under the action of the topple moment and shear stress, the brick walls above the horizontal cracks severely dislocated 7-8 mm. Otherwise, the character of the damage of the walls between upper and lower doors or windows was the same as that of intersecting diagonal shear cracks of connecting beams of shear walls. And then, the model had been damaged completely (see Figure 5 (b)).

PBM. In figure 5(c), when *V* reached 140KN, the masonry wall around windows cracked firstly, and cracks radiated and stretched to columns. At the end of cracking, V_{cr} was about 160kN, there had been ladder cracks on all sides of door-hole and window-hole. At the same time, there had been sloping cracks lined up columns and brick walls in the middle column of the first floor comprehensively. The horizontal cracks of vertical walls also developed towards horizontal walls and stretched till neighboring middle column. The cracks' width of PBM is smaller than BM greatly, obvious dislocation could be seen in the upside brick walls additionally. All above demonstrate that the bending force of prestressed forces is proficient. The destruction load Vu is 235KN (figure 5(d)). In addition, the destructive character of the connecting beams of shearing walls is similar to that of BM.

(a) Drawing of BM's horizontal walls after destruction



(b) Destruction drawing of PBM's horizontal walls



(c) Destruction drawing of BM's vertical walls

(d) Destruction drawing of PBM's vertical walls

Figure5 Destruction figures of BM and PBM

THE INFLUENCE TO ANTI-SHEARING CAPABILITY BY TOPPLE MOMENT

In List 3 and List 4,we present a comparison of displacement, anti-cracking and anti-shearing capabilities between models and sole-story-sole-piece-holed brick walls [1][3] .We know that such properties above of model BM and model PBM are higher than or near to those of brick walls WH and PWH- . But if approximately take anti-shearing capability of the horizontal walls of the former as half of the model and compare it with sole-story-sole-piece-holed brick walls, then it is lower than the latter.. Although the sticking force mechanical gnawing and pulling force of horizontal steels of brim columns with horizontal and vertical walls make models good whole ductility, several causes make horizontal wall's shearing intensity lower than the sole-story-sole-piece brick walls while its displacement high than brick greatly. Such causes are as follows: Models' material intensity is lower than holed brick wall; Produce large topple moment because of the big whole height, which result in the stress decrease of the load-bearing side and weakness of shearing intensity of masonry; Reflect shearing displacement in horizontal cracks concentrating while the shearing intensity of the place decrease because of the sticky force (so there was few slanting cracks in the low part of brick buildings); The increase of toppling moment is the increase of shearing span ratio which necessarily results in the decrease of sections' shearing intensity; the average stress under gravity of models is lower than that of holed brick walls.

Table 3. Comparison of displacement between models and holed brick walls

Displacement	Models		Holed brick walls		Ratio%
$_{cr}$	BM	11.07	WH-²	2.03	545
	PBM	10.12	PWH-II	2.85	355
$_{u}$	BM	46.19	WH-²	7.78	594
	PBM	55.41	PWH-II	17.50	317

Table 4. Comparison of intensity and shearing intensity between models and holed brick walls

Intensity	Model		Holed brick walls	Ratio %	Shearing intensity	Sole brick wall		Holed brick walls		Ratio %
f_m	BM	3.70	4.13	89.5	V_{cr}	BM	70	WH-,	115.0	60.9
	PBM	3.66		88.5		PBM	80	PWH-	162.2	40.3
$f_{v0,m}$	BM	0.283	0.311	91.0	V_u	BM	90	WH-,	158.7	56.7
	PBM	0.277		89.0		PBM	117.5	PWH-	253.6	46.3

V- HYSTERESIS CAPABILITY

We can see from Fig6 that, before cracking, hysteresis curves of the two models are both in the sharping edeged shape, and the remnant deformations and the areas covered by hysteresis curves are very small, so models are in the elastic stage. After cracking, the remnant deformation and the covered areas increase, and the structures enter into the plastic stage. When exceeding the limited loading, horizontal displacements promotes rapidly and the degradation of ductility is plumper. Meanwhile it can support larger horizontal force and consume more seismic energy under the condition of the same displacement since cracks' start and close of model PBM and the stain's change degree of vertical steels in columns both exceed model BM. So model PBM has better anti-seismic capability.

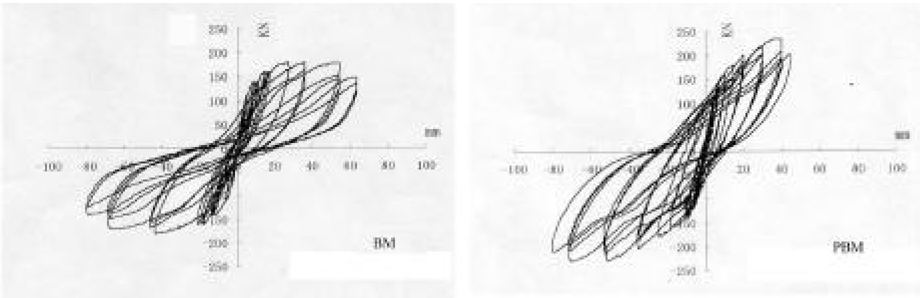


Figure 6 V- hysteresis curve of BM and PBM

Ductility

After masonry has cracked, although its strain increase very quickly, it remains a certain load-bearing capacity, which can be named as ductility and reflected with the formula of u= $_{u}/\ _{cr}$..As resprect of masonry, the top strain has the shearing-bend-strain property , so the ductility or it can reflect the ductility of the whole model to some extent. Ductility ratios of the two models in the experiment can be seen in Tab5. We discern that the cracking displacement of both models distinguish little while the cracking load of PBM is bigger than BM. Additionally, $_{u}$ of PBM exceeds BM greatly. All above indicate that the strain property of masonry increase because of the exertion of prestress force, so PBM has better ductility capability.

Table 5. Ductility ratios of models.

Model	$_{cr}$(mm)	$_{u}$(mm)	$U=\ _{u}/\ _{cr}$
BM	11.07	46.19	4.17
PBM	10.12	55.42	5.48

Displacement and deformation models

The horizontal displacement curves of the two models shown in Fig 7 and Fig 8 indicate that, as for the whole, BM and PBM have the same change regularity: Before cracking, the comprehensive horizontal displacement curve of the load-bearing side and the non-load-bearing side appear the shearing property; When horizontal pressure reaches $_{cr}$ it transmit towards bend property with the increase of the controlled displacement, the bend character becomes more and more distinctive. When $_u$=4 $_{cr}$, models damage finally, the corresponding $_u$ of PBM is bigger than BM obviously, which verify that the former has the larger strain capacity and present the shearing bend character ultimately. These are results of plastic development of models under the synonymous forces of horizontal and vertical load comprising prestress force.

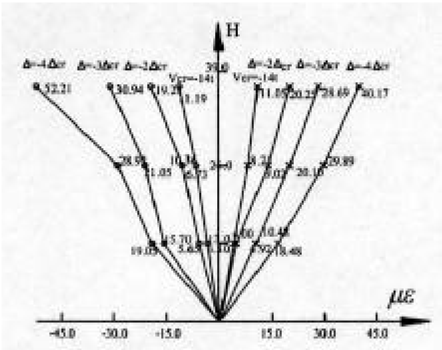


Figure7. Horizontal displacement curve of BM

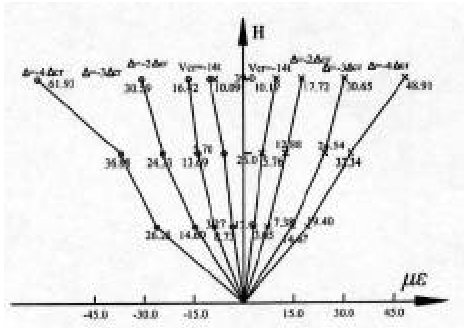


Figure8. Horizontal displacement curve of PBM

Convalescing ability

Skeleton Curve. The outer curve of *V*- hysteresis curve under every cycle is a skeleton curve, skeleton curves of the two models can be seen in Fig 9. In Fig 9, Points a and b are the start and ultimate cracking respectively, respectively; point c represents the load limitation point. Through comparison we know that the load-bearing character reflected in the skeleton curves is the same with their hysteresis curves.

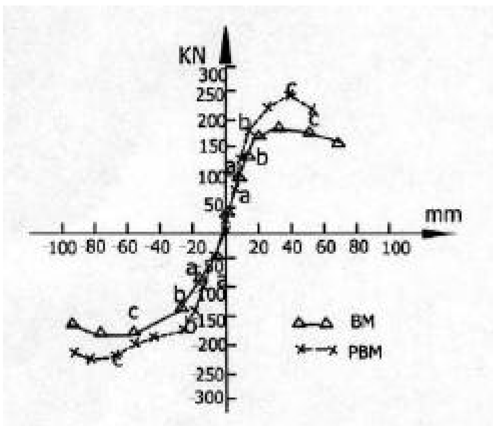


Figure9 Skeleton curve

Energy Consumption. Energy consumption is another important feature that can reflect anti-seismic of structure. We express it with the formula of $V_E = \quad E_i/V_u \quad _u$ .The practical measured results of energy consumption is shown in Table 6. Though the energy consumption ratio of PBM is lower than that of BM because of the above-mentioned reasons, the gross energy accumulation and consumption exceed BM greatly during the whole loading period.

Table 6. Practical measured ratio of energy dissipation

Model	Pushing			Drawing			Average value of $V_u \quad _u$	E_i	$UE= \quad E_i /V_u \quad _u$
	V_u(kN)	$_u$(mm)	$V_u \quad _u$	V_u(kN)	$_u$(mm)	$V_u \quad _u$			
BM	180	40.17	7230.6	170	52.21	8875.7	8053.15	11790	1.464
PBM	235	48.91	1149.385	231	61.89	14296.59	12895.22	13200	1.024

Ductility degradation. Seen from V- hysteresis curve, with the increase of circulation times and displacement degree, the ductility degradation deviation reflected by the development of plastic change can be delineated with the K_i- $_i$ curve, as shown in Fig10. Among which K_i represents the average ductility. Curve reveals that the total tendency is that the ductility depredation of the two models aggravate with the increase of $_i$. Before cracking, corresponding a certain K_i and ductility degradation of PBM is smaller than that of BM. After cracking, PBM must have a larger value of V_i or($-V_i$)in order to produce the same $_i$ of BM and the corresponding ductility of PBM is larger than BM. To sum up, whatever before or after cracking, the ductility degradation of PBM is not as quick as BM. Therefore, ductility degradation of PBM appears more relax.

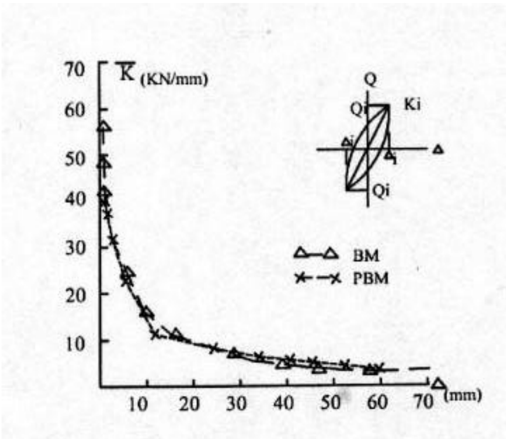


Figure10 Ductility degradation curves

Load Degradation. In fact, load degradation is another form of ductility degradation and the expressing formula is $R_{n,n+1=(}V_n\text{-}V_{n+1)}/V_n$ 100%=(1- $_{n,n+1}$) 100%, $_{n,n+1}=V_n/V_{n+1.}$ Among which n represents circulation circumference and $R_{n,n+1}$ is named load degradation coefficient between the *nth* and the *(n+1)th* circulation. By comparison we know that the load degradation of PBM and BM intensify with the increase of horizontal load. When cracking, the load degradation value of PBM is 13.44%, which is lower than that of BM's 20.79%, then the structure enter into the unstable plastic stage but remains a certain stain ability. After cracking, the load degradation value of PBM is 11.49%, which is also lower than 12.0% of BM. So the reciprocation load-bearing capability of PBM is more excellent than BM.

CONCLUSIONS

Through research on the anti-seismic capability of prestressed brick buildings, we can acquire such conclusion as follows:

(1) The cracking load and limitation load of PBM are both higher than BM. Under the condition of this experiment, the cracking load increases about 14.3% and the Limitation load increases 30.6% or so;

(2) The formation of hysteresis curves of PBM and BM are similar approximately, but the covered area of the former is bigger than the latter. As the increase of *V*, the ductility degradation of every circulation of PBM are all smaller than BM. So PBM has the better load-bearing ability and potential strain capability;

(3) The ductility and energy consumption of the prestressed masonry are both better than the non-prestressed masonry, which reveals that the prestressed masonry has the better anti-seismic capability;

(4) Horizontal displacement forms of the two models are the same, that is, the load-bearing side is of bend property and the total strain model is of bend-shearing property which near to shearing model very much;

(5) Many-storied house has approximately the similar load-shearing property as the sole-story-sole-piece brick wall under the same loading conditions. But the important distinction lies in that building models can bring into play the space superiority. On the other hand, the topple moment resulted from the increase of the whole height will obviously weaken the anti-cracking and load-bearing capabilities of horizontal walls of building models, and greatly increase their horizontal displacements. We should pay much attention to such problems in the engineering design.

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