EFFECTIVE MEASURES TO IMPROVE THE EARTHQUAKE RESISTANT PROPERTIES OF BRICK BUILDINGS

Zhou Bing-zhang[1]

SYNOPSIS: Bearing brick walls are poor in aseismic properties. They have been extensively damaged in the earthquakes. But as an economical and practicable local building material, it is still widely used in this country. About 90% of the residential buildings are built with bricks. During Tangshan earthquake, most brick buildings collapsed. However, those of 3-8 storeys with reinforced concrete built-in construction columns survived with cracks only. Through tests, investigation has been made to the damage mechanism, static and dynamic behavior of such construction. It has been proved that reinforced concrete construction columns, if properly located, will have obvious effect on preventing masonry buildings from collapse. Design and calculation approach is proposed.

Brick walls have long been used as bearing or curtain structures in constructions. In our country, masonry structures have been adopted since the Qin and Han dynasties over some 2,000 years ago. Doubtlessly, such constructions are both economical and practicable for certain localities. No matter how new building materials are developed one after another, it is impossible to abandon completely the bricks in the near future. Now, in our country, they are still widely used in constructions. For example, almost 90% of the total wall bodies in this country is still built with bricks. Indeed, they are used in large extent.

Unreinforced brick buildings, owing to their high stiffness, low strength and poor deformability, are easily subjected to damage or collapse in earthquakes even at low intensity. During earthquake in Haicheng and Tangshan the percentage of damaged buildings occurred at various intensities are listed in Table 1.

Table 1

extent of damage / intensity	slight or no damage	damaged	damaged or partly collapsed	collapsed
6 - 7	90%	10%		
8	60%	30%	10%	
9	20%	45%	35%	
10		10%	10%	80%
11				100%

Due to insufficiency in shear strength to withstand the diagonal tension developed during earthquake, the damage mechanism of the brick walls is chiefly of shear type. Under actions of cyclic reversal earthquake loadings, the wall body cracks into four pieces along the 45° diagonal directions, as shown in Figs 1 and 2.

On tall buildings of which height to width ratio is greater than 2 (i. e. $H/B>2$), horizontal cracks on lower part of the wall also appeared as caused by overturning of the whole building.

As known, it is either expensive or difficult to avoid cracks on masonry buildings under seismic load. In designing masonry buildings to withstand earthquake, besides limiting their heights, partition spacings and size of component parts etc as required by the current building code, the most important is to try to prevent sudden collapse of the building during earthquake of high intensity, thus to avoid casualties.

1 Research Engineer and Vice Head, Research Department of Beijing Architectural Design Institute.

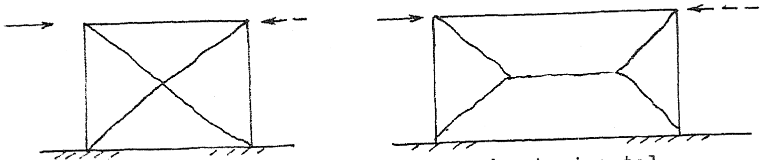

Fig 1. Cracks on brick walls under horizontal earthquake actions

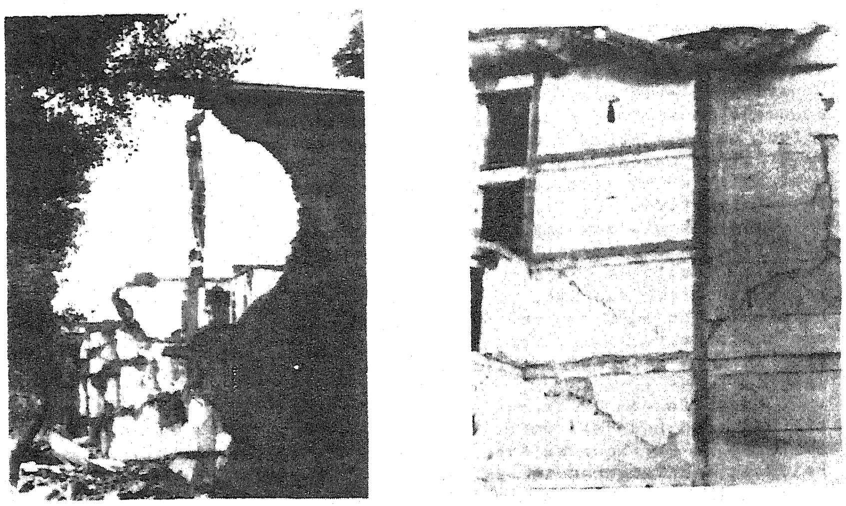

Fig 2. Brick walls damaged in Tangshan earthquake

During recent Tangshan earthquake, nearly all brick buildings of 3-8 storeys with reinforced concrete built-in construction columns proved to be capable of withstanding the shock wave with only localized damages and did not fall down. On the contrary, those without such columns collapsed almost all in the same area. It indicates practically that such constructions have particular ability to withstand the overturning action of earthquake.

After investigations have been made in that area, seven typical such buildings are listed in Table 2.

Table 2. Damage occurred on masonry buildings with reinforced concrete construction columns during Tangshan earthquake

Name	No. of storey	Location of constr cols	Cross section of the constr cols & reinforcements etc	Description
Xinhua Hotel	8	inner frame, constr cols arranged along outer walls spaced at 3-8 m	constr cols: 40x47 cm reinforced with 4Φ22 and Φ6-20 stirrups middle cols: 50x50 cm reinforced with 4Φ25, 2Φ16, 6Φ22 and Φ6-20 stirrups	middle col head on the 4th floor crashed with bars buckled, floor slabs sunk several tens cm, some partitions fell down, outer walls basically in good condition, except holes formed on the 4th floor due to collision

Main Building of Cement Design Institute	7	inner frame, constr cols arranged along outer walls spaced at 3.5-7 m	constr cols: 37x55 cm reinforced with 8 Φ18, 2 Φ12 & Φ6-25 stirrups 50x50 cm (cross shape) reinforced with 6 Φ18, 4 Φ12 & 6-25 stirrups middle cols: 45x45 cm reinforced with 16 Φ25 & Φ8-30 stirrups (1st to 4th floor)	outer col heads sheared to damage at the ground fl, constr cols stripped from walls (cols on ground fl cast prior to the walls), cols above the 1st fl were in good condition, the 6th fl was under construction
Book Storage of Mineral Academy	4	inner frame, constr cols spaced at 3.75 m along outer walls	constr cols: 25x25 cm reinforced with 4 Φ14 & Φ6-20 stirrups middle cols: 35x35 cm	1st fl collapsed down torsionally, upper 3 floors lowered downwards with slight damage
No. 422 Cement Plant Office Building	3	masonry constr, inner corridor in the middle with constr cols at wall junctures	constr cols ground floor: 25x25 cm with 6 Φ19 and Φ6-20 stirrups 1st floor: 25x38 cm with 6 Φ19 and Φ6-20 stirrups 2nd floor: 25x38 cm with 4 Φ16 and Φ6-25 stirrups	bricks broke down from wall piers where there were constr cols, fl loads carried by constr cols
Tangshan Building for Foreign Guests	5	constr cols at staircase wall and outer end wall corners	at outer wall corners: 30x36 cm reinforced with 4 Φ20 & Φ6-25 stirrups at staircase: 30x36 cm reinforced with 4 Φ19 & Φ6-20 stirrups	walls slightly damaged where there were constr cols, walls collapsed or seriously damaged where there were no such cols
Office Building on Xinhua Road	5	constr cols at middle portion entrance hall and staircase, extended to 2nd floor	ground to 2nd fl: 36x36 cm reinforced with 4 Φ16 & Φ6-20 stirrups, wall beams are provided on every fl, cols tied to walls	ground to 2nd fl with constr cols did not fall down, while the 3rd and 4th fls collapsed
Second Light Industry Bureau Office Building on Xinhua Road	5	constr cols at middle portion entrance hall, wall beams on every floor, cols tied to walls with 2 4 bars at 50 cm	constr cols (outer cols): 62x70 cm with 4 Φ20, 2 Φ16 & Φ6-25 stirrups inner cols: 40x40 cm with 4 Φ20 & Φ6-25 stirrups 50x50 cm with 8 Φ16 & Φ6-25 stirrups	top storey fell down while others in good condition

As indicated by the experience gained on ferocious earthquake that the effect of construction columns is obvious, the shaken walls will not totally lose their load bearing capacity even though wall bodies are cracked to damage or approaching collapse, provided that there are wall beams built on every floor and tied with the construction columns. Thus, danger of sudden collapse of floor slabs during earthquake can be avoided.

Tests were made to further investigate from their damage mechanism, how to design and calculate the construction columns for better structural arrangement. We made 35 pieces of 2000 x 92 cm single wall bodies for horizontal cyclic reversal loading tests and 3 models of 1:4 in scale for static and dynamic shock tests. Results obtained are as follows:[2]

1. Main Results from Static Tests.

(1) Horizontal load bearing capacity of single wall with construction columns can be raised by 56 - 60 % more than those without. If low grade mortar is used in the wall, then capacity raised will be 23%.Moreover, the more the vertical stress is, the more the horizontal load bearing capacity will be raised.

(2) Monolithic model tests show that with construction columns initial crack load strength can be raised by 51% and damage load strength by 55%.

(3) Stress in reinforcement: Before cracking, the wall body worked jointly with the construction columns, thus, relation between load and steel strain was linear. After cracking, however, it became nonlinear. Stress of steel on the tension side raised more rapidly, while that on the compression side changed but few.

(4) Stiffness and ductility: Test specimens' stiffnesses decreased significantly with increasing of their lateral displacements. Construction columns have little effect on monolithic stiffness. The ductility factor is obtained through the condition that energy absorption is in equilibrium. Without construction columns, the ductility factor of the whole model was found to be $\mu = 1.81$, while models with columns $\mu = 3.43$ and 3.93.

It can be seen from comparing the hysteresis loops atop the 3 models that the area covered by those with columns is far more than that without, which indicates that absorption of energy was improved significantly. (see figs 3)

(5) Cracking and damaging characteristics: Comparison of tests shows that initial crack loading capacity of the models with columns were raised, and that cracks were limited only on the ground storey for model without columns, while they were extended to 2nd and 3rd storeys for those with columns, which indicates that both monolithic property and uniformity of the structure was improved, thus beneficial to withstanding earthquake.

2. Main Results Obtained from Dynamic Excit Tests:

(1) Dynamic characteristics are listed in Table 3.

It can be seen from table 3 that:

(a) Frequency at damaging stage is cecreased by 1.63 times from that of before cracking for model without columns, and 1.83 - 4.16 times for those with columns.

(b) Damping factor of the model with columns at damage stage increased to 2.25 times that of before cracking, while without columns, only increased 1.5 times.

(c) Mode of vibration: Mode of vibration was basically the shear type for all models.

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2 Partakers of these tests are: Research Department of Beijing Architectural Design Institute, Aseismic Research Institute of Academy of Building Sciences, Department of Architectural Engineering of Tsinghua University, Institute of Engineering Mechanics, Beijing 1st and 5th Construction Companies, Housing Administration Bureau of Beijing, etc.

Table 3

Stage		Elastic			Plasto-elastic			Damage			Collapse
Method		resonance	sudden release	pulse	resonance	sudden release	pulse	resonance	sudden release	pulse	resonance
Model I with columns	frequency	19	25	25.5	14	20	24.2	-	6	9.5	1.8-3
	damping facter		0.067		0.073	0.082			0.15		
Model II without columns	frequency	17.6	20	25	16.2	18.6		10.8	>11		sudden collapse
	damping facter	0.068	0.067		0.086	0.083		0.10			
Model III columns added	frequency	19	23	23.4	16	20		10	10	12.8	2 - 3
	damping facter	0.08	0.076		0.11	0.10		0.068	0.12		

Note: **frequency in Hertz.**

(2) **Ultimate deformation:**

During **excitation, model without columns** collapsed when top displacement **reached 0.83/100; while models** with columns still remained when top **displacements reached** 1.67/100 and 1.17/100 respectively.

(3) **Mode of collapse:**

For model without columns, sudden collapse occurred **under** excitation; **while on those with columns cracks and damages were uniformly distributed all over and remained uncollapsed upto an excit load corresponding to intensity 9.**

3. **Discussion on Method of Calculation.**

It shows experimentally that when brick walls are provided with **construction columns, the structure is** still **governed by shear. Of course, construction columns are not only acted by shear but also subjected to bending. However, as observed from the mode of vibration, for lowrise (≤ 4 storeys) and stiff buildings (with partitions on every bay) with construction columns, shear is the main cause of deformation.**

Shear strength of the brick body with construction columns consists of 3 parts: i. e. masonry, concrete columns and reinforcement. Therefore:

$$Q_p \leq \frac{R_{\tau} A}{\xi} + 0.07\, R_h A_h + A_g R_g$$

where ξ - uneven factor of shear in masonry;
α - a factor of 0.2 - 0.25, in accounting for shear strength in reinforcement;
R_h, R_g - compressive strength of concrete and tensile strength of steel of the construction columns respectively;
R_{τ} - shear strength of masonry, $R_{\tau} = R_j \sqrt{1 + \frac{\sigma_o}{R_j}}$;
A - area of the masonry taking shear;
A_h, A_g - cross sectional area of construction column and reinforcement respectively.

As indicated through analysis of test results, area of construction columns is relatively small in portion as compared with that of the masonry, therefore, the shear strength of the column concrete can be neglected. After introducing factor of safety into the expression, we obtain the following formula for shear strength of the brick wall with construction columns:

$$K_p Q \leq \frac{R_{\tau} A}{\xi} + 0.4\, R_g A_g$$

where K_p - 2.5 x 0.8 = 2, safety factor accounting for seismic consideration;
0.4 - when K_p = 2.5, factor for raising steel strength in structure is 2.5/1.55 = 1.6, then multiplied by a factor of 0.25 and thus obtain the result.

It is necessary to point out that the shearing stress in the steel is not developed at the same time as that in the masonry. In the early stage, shearing force is mainly carried by the masonry, while stress in the reinforcement is small. After cracking of the wall body, the reinforcement comes into action. According to the test results, we take the influence factor of shearing strength of reinforcement to be 0.25.

4. Construction Measures.

(1) Arrangement: On the plane, construction columns should be placed at intersections and corners of longitudinal and cross bearing walls, and at locations where loading is concentrated or where sectional area of the brick pier is small. At the inner wall corners of rooms with small bays, such columns may be omitted or reduced in number. Construction columns should be extended from the footing or foundation beam continuously upwards to the roof.

(2) Connection: Reinforcements in the construction columns should be tied to those of the wall beams on every storey. Top of the columns should be tied to the roof wall beams. If columns come across a girder, their reinforcements should also be tied together. Between the columns and the wall body, tie bars of 2Φ6 or 2ϕ8 should be provided in the brick joints at every 50 cm high along the column and extended 100 cm from either side of the column for better connection.

(3) Cross section and reinforcement: The smallest sectional area of construction columns should be 18 x 24 cm with due enlargement at corners. The reinforcement should be no less than 4 ϕ 12, while for corner columns, no less than 4 Φ 14. The stirrups' spacing should be no greater than 20 cm.

(4) Construction: Brick walls should be laid before concreting of columns. The end of walls next to columns had better be laid staggered so as to increase the integrated bonding between the wall and column. Grade of the bricks used should be no less than 75, and with mortar no less than 25.

Conclusion:

As masonry constructions shall be still widely used in seismic regions, measures must be continuously sought to increase the earthquake resistance of such constructions.

Reinforced concrete construction column is a kind of anti-collapse safety measure for masonry construction to withstand the earthquake shock. Its effectiveness has been proved through Tangshan earthquake. Further investigations are to be made to promote and solve the problems regarding how to design and calculate such structures for that purpose.

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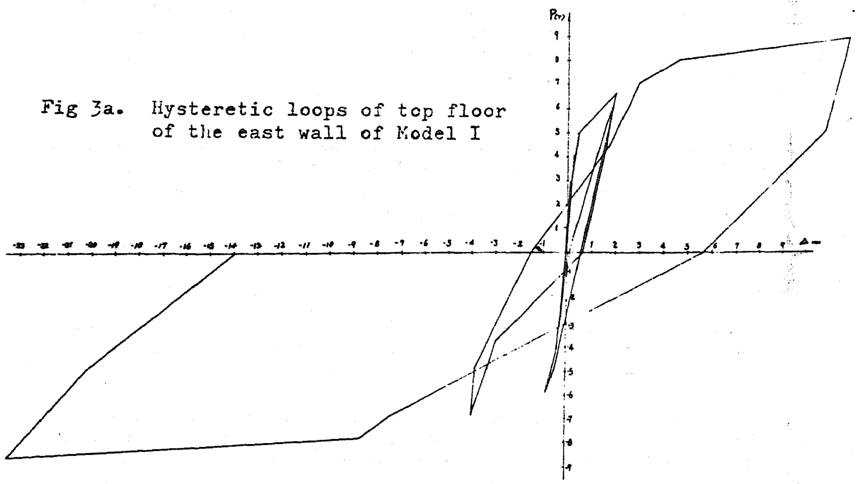

Fig 3a. Hysteretic loops of top floor of the east wall of Model I

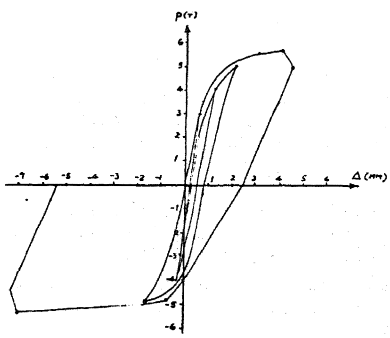

Fig 3b.

Hysteretic loops of top floor of the east wall of Model II

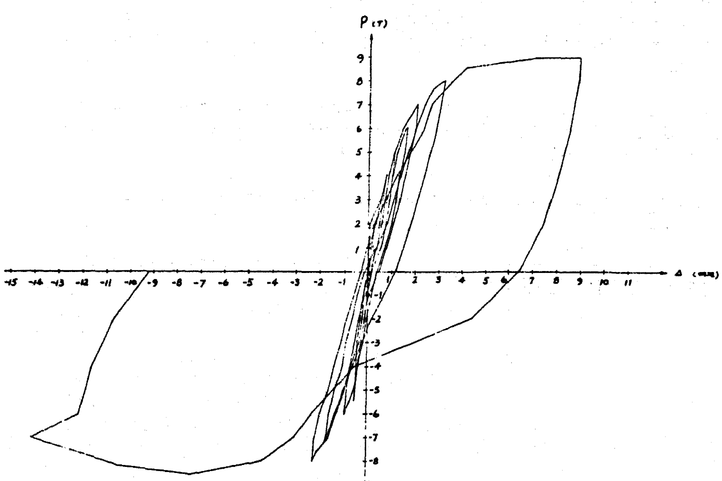

Fig 3c. Hysteretic loops of top floor of the east wall of Model III