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EARTHQUAKE REACTION ANALYSIS OF A NEW TYPE OF MULTI-STORY ENERGY-CONSERVATION MASONRY STRUCTURE

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ABSTRACT

A new type of masonry structure with interior brick and external aerated concrete block is reported here, which integrates the advantages of both block wall and brick wall into one entity, such as energy-saving, economical, and easy for construction, etc. Earthquake reaction analysis on a seven-storied dwelling house with this new type of structure is conducted, analyses indicate that this new structure is suitable for earthquake zone, and can be popularized.

KEYWORDS: Hysteretic curve, Shear stress, Inter-storey displacement

INTRODUCTION

Energy conservation is one of the important considerations for studying and developing new types of wall materials and new types of structural systems. According to the Energy Conservation Design Standard for Civil Architecture (JG726-95) [1], the requirement for energy conservation is as high as 50%. Among wall materials available, only aerated concrete block can meet this requirement. Because no combination with others building materials is needed, the construction of structures with this wall material is easier and cost is lower. A lot of energy-conservation buildings constructed of aerated concrete block have been built all over China. For the purpose of the popularization and application of this kind of building in earthquake zones, the China Northeast Architectural Design and Research Institute and other researchers have conducted studies on the earthquake-resistant behaviour of buildings constructed of aerated concrete block. Nonetheless, looking back at the development process, the application of this type of new structure hasn't been greatly popularized. The main reason is that the cost of aerated concrete is higher than that of commonly used clay brick. If the aerated concrete block is used both for interior walls and for external walls of a masonry building, the one-time investment is a bit higher than that with solid bricks, and the construction method is different from the traditional method. Therefore, this type of structure has not been widely accepted. However, the new type of structure with interior brick and outer aerated concrete block has the advantages of both brick and aerated concrete structures, which can reduce the cost, achieve the energy conservation aim, and the construction method is the same as the traditional one. This is a new type structural system for the purpose of energy-conservation.

In earthquake zones, the interaction and deformation compatibility between the brick and aerated concrete block walls in the new system are of greater concern. Therefore, earthquake-resistant behaviour needs to be studied. According to the principle of "No collapse in large earthquakes, repairable in medium earthquakes, no cracking in minor earthquakes" demanded by the current Chinese earthquake-resistant design standard, various earthquake spectra were utilized to conduct earthquake reaction analysis. Meanwhile, simulated earthquake experiments of structures were conducted, which has provided an earthquake-resistant design basis for multiple-story buildings with interior bricks and external aerated concrete blocks.

DEFINITION OF PARAMETERS FOR EARTHQUAKE REACTION

To conduct nonlinear seismic analysis on the structure, the first step is to choose a practical restoring force model. The restoring force model for an "interior brick and external aerated concrete blocks" structure is determined by the restoring force feature of the walls which carry shear force.

Factors Influencing Earthquake-Resistant Behaviour of Walls

According to experiments on reinforced brick walls and reinforced aerated concrete block walls, the main factors that influence the performance of force resistance of walls and hysteretic curve features are summarized below:

The influence of vertical compressive stress

Vertical compressive stress has effectively improved shear strength of walls, and provides certain confinement for deformation. For reinforced walls as well as unreinforced walls, the shear strength proportionally increases with vertical compression stress to a certain extent.

The influence of strength of masonry

The shear strength of reinforced walls is determined by the strength of the masonry itself. Improving appropriately the strength of block and mortar can enhance the strength of masonry and the shear strength of walls.

The influence of reinforcement ratio and supporting beam

Maximum shear strength and maximum deformation increase obviously with the increase of reinforcement ratio, and the strength margin has an increasing trend after walls crack. The maximum displacement of reinforced brick walls is 2~3 times that of unreinforced brick walls, whereas maximum displacement of reinforced aerated concrete block walls is 2~2.5 times that of unreinforced aerated concrete block walls. Reinforced concrete supporting beams also have a confining effect on walls, and can improve the shear resistant capacity of walls, especially the deformation behaviour of walls.

The influence of depth-to-width ratio of wall and openings

With an increase in depth-to-width ratio of walls, the bearing capacity of the wall decreases correspondingly and the deformation increases. The presence of openings decreases the maximum shear force resistance of walls, whereas the maximum deformation increases, that is, lateral shear stiffness decreases. Therefore, the depth-to-width ratio and wall-window ratio should be controlled.

Hysteretic Curve and Restoring Force Model Used in Earthquake Reaction Analysis

Figure 1 and Figure 2 are typical hysteretic curves of the brick walls with horizontal reinforcement and the aerated concrete block walls with horizontal reinforcement and supporting beam under cycling load. The envelope curve of these hysteretic curves is the lateral resistance envelope of such walls. The least squares method was used to obtain the restoring force curve from experiments.

The envelope consists of three stages (three straight lines) as shown in Figure 1 and 2: the first stage is elastic stage, the end point of which is the cracking load P_c and the corresponding displacement is Δ_c; the second stage is elastic-plastic stage, the end point of which is the maximum load $P_{u,}$ and the corresponding displacement is Δ_u; the third stage is failure stage, the end point of which is the failure load of wall $P_{w,}$ and the corresponding displacement is Δ_w. The experimental results were normalized. A three-line restoring force model was obtained, as shown in Figure 3 and 4. The equations for the three stages for the brick wall with horizontal reinforcement are:

First stage:

$P/ P_{u,}=2.48\ \Delta/\Delta_u$ Equation 1

Second stage:

$P/ P_{u,}=0.333\ \Delta/\Delta_u +0.667$ Equation 2

Third stage:

$P/ P_{u,}=-0.214\Delta/\Delta_u +1.214$ Equation 3

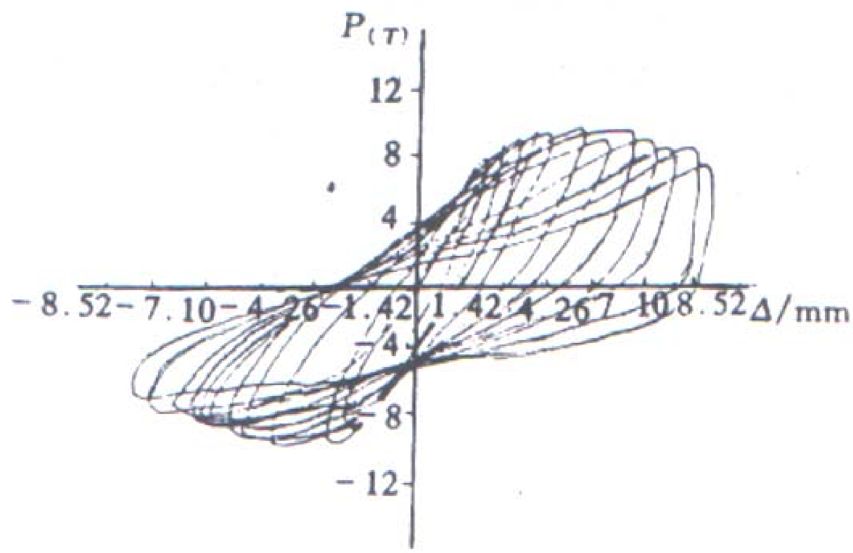

Figure 1 – Typical hysteretic curve for reinforced brick walls

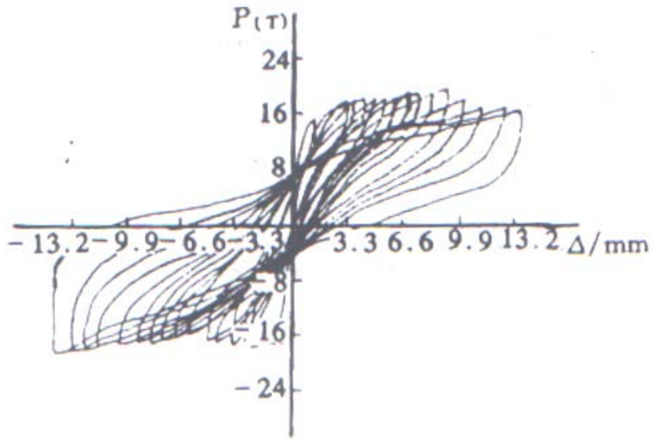

Figure 2 – Typical Hysteretic Curve for Reinforced Aerated Concrete Block Wall with Supporting Beam

The equations for the three stages for the Aerated concrete block wall with horizontal reinforcement and supporting beam are:

First stage:

$P/P_{u,}=1.64\Delta/\Delta_u$ Equation 4

Second stage:

$P/P_{u,}=0.36\ \Delta/\Delta_u+0.64$ Equation 5

Third stage:

$P/P_{u,}=-0.113\Delta/\Delta_u+1.113$ Equation 6

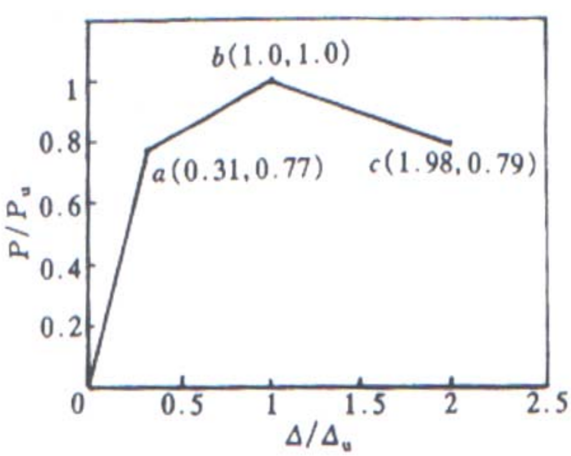

Figure 3 – Envelope for Reinforced Brick Wall

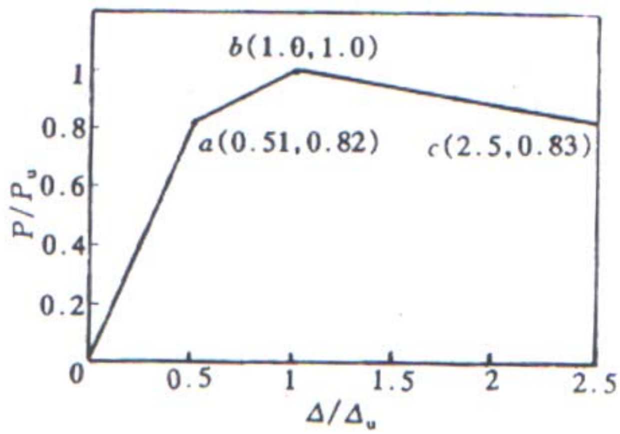

Figure 4 – Envelope for Reinforced Aerated Concrete Block Wall with Supporting Beam

SELECTION OF MAIN PARAMETERS FOR EARTHQUAKE REACTION ANALYSIS

Earthquake reaction analysis was conducted for a seven-story energy-conservation dwelling building with "interior brick and external aerated concrete block" structure designed by China Northeast Architectural Design and Research Institute. The thickness of external wall: 300mm, thickness of interior wall: 240mm, height of window: 1.5m, height of door: 2.2m, height of ground floor: 3.1m, height of the seventh floor: 3 m, height of other floors: 2.8m.

According to Load Code for the Design of Building Structures (GB 50009□2001) [1] and Standard for Seismic Design of Structure (GBJ11—89) [2], the loads applied to each floor were taken as follows: load at ground floor is 4290 kN, load at the seventh floor is 3606 kN, and load at the other floors is 4137 kN. The ultimate load for brick walls with lateral reinforcement is determined as:

$$P_u = (f_{VE}\,A + 0.15\,f_y\,A_s)/r_{RE} \qquad \text{Equation 7}$$

Where r_{RE} is the seismic adjustment factor of bearing capacity, taken as 0.9; f_{VE} is the seismic shear strength design value of the building for failure along stepped cross section, $f_{VE}=\zeta_N f_V$; ζ_N is the influencing coefficient of normal stress on masonry strength based on Standard for Seismic Design of Structure (GBJ11—89) [2]; f_V is a design value of shear strength of masonry without consideration of seismic design based on Standard for Design of Masonry Structure (GB50003-2001) [3]; A is cross-sectional area of wall; f_y is a design value of tensile strength of reinforcement; A_s is total cross sectional area of reinforcement.

According to experimental results

$$P_c = P_w = 0.85\,P_u\ ,\ P_t = 0.5P_u \qquad \text{Equation 8}$$

Where P_c is load at cracking of wall, P_w is load at wall failure, and P_t is load during elasticity.

For aerated concrete block walls with horizontal reinforcement, according to previous experimental results on nine walls, the ultimate load P_{ua} is expressed:

$$P_{ua} = R_r A/\zeta \qquad \text{Equation 9}$$

Where R_r is the seismic shear resistance of aerated concrete block walls:

$$R_r = (0.65+0.29B/H)R_{p1}(1+\sigma_0/R_{P1})^{1/2} \qquad \text{Equation 10}$$

Where A is the cross sectional area of block wall; ζ is the non-uniformity coefficient of shear force of section, taken as 1.2; B/H is the depth-to-width ratio of the wall; R_{p1} is cleavage strength of concrete block, σ_0 is normal stress of wall.

According to experimental results:

$$P_c = P_w = 0.8P_u,\; P_t = 0.5P_u \qquad \text{Equation 11}$$

Mortar strength is based on design values. For block walls, the mortar strength is: M10 for the 1st floor, M 7.5 for the 2nd and 3rd floors, M5.0 for 4th~7th floors; and for brick walls, M10 for the 1st floor, M 7.5 for the 2nd and 3rd floors, M5.0 for 4th floor, M 2.5 for 5th~7th floors.

SHAKING TABLE TEST AND SELECTION OF EARTHQUAKE RECORDS

In order to investigate the seismic capability of a seven-story energy-conservation dwelling building with interior brick and external aerated concrete block structure, a 1/6 scaled model was tested with a shaking table. El-Centro and Ninghe seismic spectra were used. According to the relationship of similarity, the time axis of the original earthquake record time is scaled down by 2.45 times, coefficient similarity for acceleration is 2, and coefficient similarity for displacement is 6. Floor 1~floor 3 were reinforced according to actual reinforcement ratio used in original masonry structures. Comparison between the experimental results and earthquake reaction analysis results was made. Agreement between the two is good.

The selection of earthquake records depended on the type of field soil. In earthquake reaction analysis, two representative earthquake spectra were used—El-Centro, and Ninghe as listed in Table 1.

Table 1 – Earthquake Record

No	Name of earthquake	Magnitude (M)	Time	Place of record	Peak acceleration (cm/s^2)	Excellent field soil	
						Cycle	Type
1	Imperial Valley	7.0	May 18, 1940	El-Centro	341.695	0.55	II
2	Ninghe	7.1	Nov. 15, 1976	Tianjin Hospital	145.805	0.90	III

RESULTS OF EARTHQUAKE REACTION ANALYSIS OF SEVEN-STORY ENERGY-CONSERVATION DWELLING

The following assumptions have been made in the earthquake reaction analysis:

1. The mass of each upper and lower 1/2 storey is concentrated to the each floor level;
2. To neglect the deformation of floor itself, the floor has infinite rigidity in its own plan;
3. The floor displaces in horizontal direction, axial deformation of walls is neglected, and structure is built in rigid foundation;
4. Horizontal reinforcement in walls only bears tensile stress;
5. Effect (strength, displacement) of reinforced concrete supporting beam is only considered in restoring force model.

An elasto-plastic analysis program provided by the Engineering Mechanics Research Institute of State Seismological Bureau was used in the earthquake reaction analysis of a seven-story energy-conservation dwelling house. Figure 5 and Figure 6 present the maximum earthquake shear force reaction and the maximum inter-storey displacement of the building along the transverse wall. Earthquake reaction of building along the longitudinal walls is listed in Table 2.

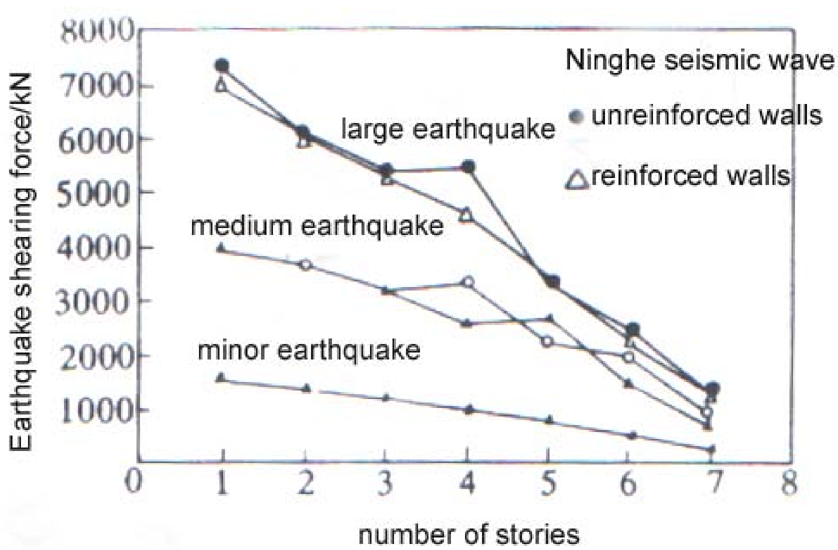

Figure 5 - Maximum Earthquake Shear Force Reaction of Building along Transverse Wall

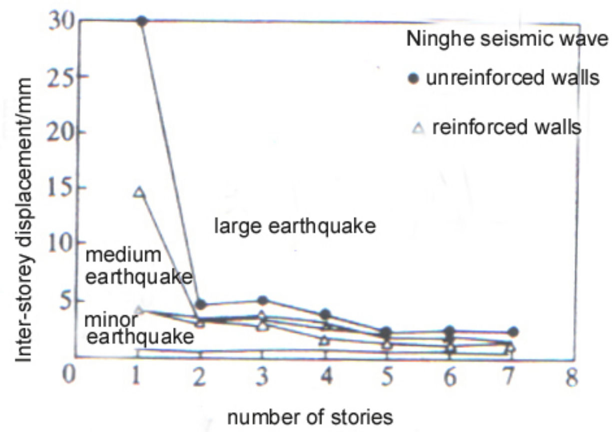

Figure 6 – Maximum Inter-Story Displacement of the Building along Transverse Wall

Table 2 – Earthquake reaction of building along longitudinal walls

	Type	Design status	1st floor	2nd floor	3rd floor	4th floor	5th floor	6th floor	7th floor
Earthquake Shear Force	Great earthquake	Earthquake Reaction shear force /kN Pu /kN	4898 4900	4375 4390	3517 4170	2950 2970	2569 2670	2018 2400	1195 2120
	Medium earthquake	Earthquake Reaction shear force /kN Pc /kN	1.74 3920	1.64 3570	1.63 3330	3.33 2380	1.86 2130	1.85 1920	1.73 17000
	Minor earthquake	Earthquake Reaction shear force /kN Pt /kN	1718 2450	1597 2200	1466 2090	1253 1490	997 1340	690 1200	334 1060
Inter-Story Displacement	Great earthquake	Earthquake Reaction shear force/kN Δ u /kN	13.10 13.86	4.60 11.90	2.60 15.26	4.26 8.96	3.30 8.12	1.85 11.56	2.83 4.15
	Medium earthquake	Earthquake Reaction shear force/kN Δ c /kN	1.74 3.94	1.64 4.14	1.83 4.34	3.33 4.56	1.86 4.12	1.85 5.88	1.73 7.89
	Minor earthquake	Earthquake Reaction shear force/kN Δ t /kN	0.059 0.197	0.053 2.05	0.064 2.16	0.082 2.27	0.065 2.07	0.075 2.94	0.073 5.46

COMPUTATION RESULTS AND DISCUSSIONS

1. **Transverse and longitudinal seismic capacity of building**
   It is shown that the longitudinal seismic capacity of the building is less than than the transverse seismic capacity of building. Under El-Centro and Ninghe seismic spectra, the transverse walls of each story (unreinforced) are in the elastic stage in minor earthquakes. In large earthquakes, those on the 1st floor to the 3rd floor crack but don't collapse. It indicates that the transverse walls meet the seismic requirements. Unlike the transverse wall, the longitudinal walls on the 1st floor to the 3rd floor need to be reinforced to meet the seismic requirement.

2. **The influence of reinforcement on earthquake reaction**
   Horizontal reinforcement and supporting beams enhanced the seismic behaviour of the building, and the displacement reaction is better than shearing force reaction of the building.

3. **The influence of various seismic waves**
   The Influence of the Ninghe record on the earthquake shear force reaction of the building is a bit bigger than that of El-Centro, whereas displacement reaction under Ninghe is much bigger than that under El-Centro. As for acceleration reaction, that under El-Centro is 11% higher than that under Ninghe in both transverse and longitudinal directions.

CONCLUSION

From the earthquake reaction analysis results and experimental results on 1/6 scaled model, it indicates that both transverse and longitudinal walls in this new type of structure meet the "three level" requirement for seismic design, that is, no collapse in large earthquakes, repairable in medium earthquakes, no cracking in minor earthquakes. It shows that a seven-story dwelling building with an "interior brick and external aerated concrete block" structure can be built in earthquake regions with magnitude of up to seven, but the following measures in the structure must be taken:

1) The mortar strength should be selected as follows: for block walls, M10 for the 1^{st} floor, M 7.5 for the 2^{nd} and 3^{rd} floors, M5.0 for 4^{th}~7^{th} floors; for brick walls, M10 for the 1^{st} floor, M 7.5 for the 2^{nd} and 3^{rd} floors, M5.0 for 4^{th} floor, M 2.5 for 5^{th}~7^{th} floors.
2) The horizontal reinforcement in walls can greatly improve deformability of buildings, that is, it can control the inter-storey displacement of buildings and enable stories with cracks not to collapse. The suggested number of stories with horizontal reinforcement is one to three, and the suggested reinforcement ratio is 0.07%~0.017%.
3) A wall thickness of 370 mm should be used for a single layer interior longitudinal wall, and a thickness of 480 mm should be used for double layer interior longitudinal walls (240 mm for each).
4) The weak link for supporting beams is located at the ground floor, so the reinforcement of ground floor supporting beams should be increased from 4 12 mm bars to 4 14 mm bars.

In short, it is fully feasible to build seven-storied energy-conservation dwelling buildings with "Interior brick and external aerated concrete block" structure in earthquake region with magnitude of 6~7. This new type of structural system may be greatly popularized and applied, and it will bring immeasurable economic benefit and social benefit to the society.

REFERENCES

1. Load Code for the Design of Building Structures (GB 50009- 2001), China Ministry of Construction, Beijing, 2002.
2. Standard for Seismic Design of Structure (GBJ11—89), China Construction Industry Press, Beijing, 1990
3. Standard for Design of Masonry Structure (GB50003-2001), China Construction Industry Press, Beijing, 2002.
4. Standard for Energy Conservation Design of Structure (JGJ26—95), China Construction Industry Press, Beijing, 1996.