11 WCEE
Paper No. 662. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

MEDIUM AND HIGH-RISE MASONRY CONSTRUCTION IN CHINA-RESEARCH AND APPLICATION OF COMPOSITE MASONRY WALL SYSTEM

R. F. WU

Dept. of Engineering Mechanics
Dalian University of Technology
Dalian 116024, China

Q. G. ZHANG

Building Design and Research
Institute of Liaoning Province
84 Heping South st.,
Shenyang 110005, China

ABSTRACT

The reinforced concrete confined beams and columns are used not only to restrain the brick/block masonry, but also to strengthen the composite walls. The confined beams and columns would act as a part of the wall element to resist both the vertical and horizontal loading actions. The advantages include simpler construction procedures and a 15～25% reduction of cost than the R. C. Frame buildings. The static and dynamic model building tests have shown that they exhibit good integration and earthquake resistant performances. The nonlinear elastic finite element method for analyzing the composite walls is briefly introduced and a comparison between the calculations and wall tests showed that this method would provide a good application as the simplified formulas with acceptable accuracy both for cracking and ultimate shear strength of the composite walls. The elastic-plastic analyses of dynamic response and reliability for a 8-stroey composite masonry wall building showed that this new masonry wall system building could be safely constructed in the seismic zone with an earthquate intensity of 7 to 8.

KEYWORDS

Composite wall; confined beam and column; static wall test; Nonlinear elastic finite element method; Dynamic model building test; Dynamic reliability.

INTRODUCTION

More than 80% of the total building area in China are occupied by the brick masonry buildings. It is well known that unreinforced brick masonry buildings suffered a fatal weakness-their britteness. They are easily damaged and even destroyed under severe earthquake motions. So to have their seismic resistance improved is of urgency and great significance. The basic bearing element of brick masonry building is the brick wall. That is why the studies of improving aseismic performance of brick wall are so important. A brick wall possesses great bearing strength but little ductility. Under the reciprocating motions of earthquake, once being cracked, it will easily break apart. Ameliorative measures would be taken to reinforce it and fasten the ties between walls. There are many ways to reinforce a brick wall: The first is by planting the brick/block holes with vertical steel reinforcements and are then grouted with concrete. The second, for solid or hollow brick walls, the steel reinforcements are planted in horizontal mortar joint. The third one is to build so-called constructional columns at the two ends of the wall. The purpose of using these RC columns is to delay the breaking duration of the cracked brick masonry and to improve the ductility of the wall. The promising effects of such measures was exhibited during the Daofu Earthguake in Sichuan province (Richter Magnitude 6. 9, 1981. 1. 24). Based on a study on brick masonry building with constructional columns (Wu et al. , 1982) a further development the concept of composite masonry is thus put forward, that is to say that should the confined RC beams and columns not break apart from masonry until the wall is collapsed, their contribution to the resistance of compression, tension and shear like masonry may also be effective. Walls, as a single structural element, made of these two different materials and members, RC columns, beams and masonry, are called composiste masonry wall in current paper. Several million square meters of 7 to 9-storey residence buildings have been built around some cities in seismic zones with an earthguake intensity of 7 and 8 since 1987.

EXPERIMENTAL STUDY

The goal of the composite wall tests was focused on the capability to resist lateral load and stress distribution between columns and masonry under vertical load for transvers wall with columns at their middles and longitudinal walls with windows.

Two groups of transverse model walls in a scale of 1 : 2 with dimensions of 1400×2750×120mm, each of which has three columns whose cross section is 200×120 mm with reinforcements of 4ϕ8 and 2ϕ6 (Fig. 1).

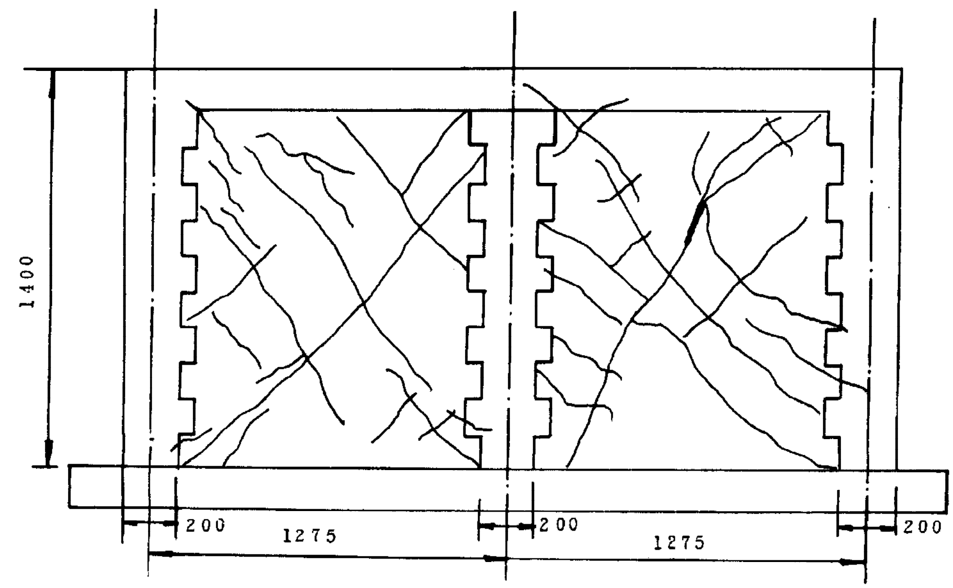

Fig. 1 Transverse model wall HC-1a

Table 1 Comparison Between Calculated and Observed

Speciman	Cracking				Failure			
	Load kN		disp. mm		Load kN		Disp. mm	
	Exp.	Cal.	Exp.	Cal.	Exp.	Cal.	Exp.	Cal.
HC—1	200	200	0. 14	0. 13	325	366	0. 47	0. 45
HC—2	180	190	0. 10	0. 12	310	352	0. 33	0. 47
SZ—1	340	255	0. 31	0. 14	565	705	1. 4	0. 53
SZ—2	350	275	0. 24	0. 16	526	603	1. 35	0. 47
ZC—1	51	57	0. 10	0. 07	81	99. 8	0. 32	0. 21
ZC—2	48	46	0. 06	0. 06	76	78. 1	0. 22	0. 16

The difference between the two groups is that the smaller cross section of 120×120mm and reinforcement of 4ϕ6 for the middle column of the walls in the second group. The masonry is made of special 1 : 2 model brick. The walls were under vertical stress of 0. 41MPa and the horizontal load alteratively acted on the two ends of confined beam and increased with each loop until collapse took place. Results are shown in Table 1.

By examining the cracks of the walls it revealed, two x-shaped cracks were formed (Fig. 1) if the middle column is strong. This is indicates that the middle column play the major role in resisting propagation of the cracks. While the middle column is weak, the nature of cracking is similar to that of walls without the middle column. At the limit state, cracks would penetrate through the middle column from masonry of either side. HC—1 gives a lateral strength of 12—14% higher than HC—2.

The Ductility Coefficient of Walls is About 3. 5.

Two full scale longitudinal walls SZ—1 and SZ—2 in size of 2800×6840×370mm with three confined columns of cross section 400×240mm and reinforcements of 4ϕ16 and 2ϕ12 were examined. There are also two windows (1800×1500mm) on each wall. Two groups of 1 : 4 scale model walls ZC—1 and ZC—2 in size of 700×2575×92. 5mm with three windows in 450×375mm and 375×375mm in SZ—1 and SZ—2 respectively were examined.

Cracks begin to appear at the bottom corners of the windows and be gradually developed inclined between the windows. This crack propagation would extend to the columns and be arrested by them. But at limit state, these inclined cracks would penetrate into those coulumns (Fig. 2). Test results are listed also in Table 1. Typical crack pattern is shown in Fig. 2.

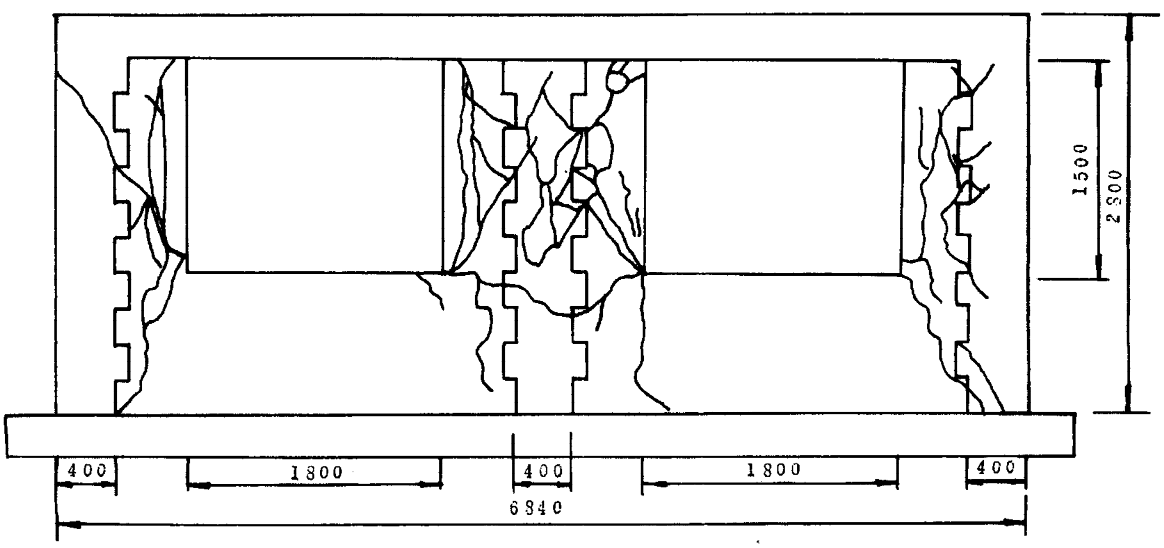

Fig. 2 Longitudinal model wall ZC—1

The ductility coefficients of 1 : 1 and 1 : 4 model walls are about 5 and 3. 6 respectivety. Small scale model walls provide obviously the size effect. Their lateral strengths are increased by about 10～15% for 1 : 2 model walls and about 20～25% for 1 : 4 model walls. Such phenomenon should be considered in the test of small scale model walls.

Test of 1 : 2 8-Storey Composite Wall Model Building

A 8-storey composite wall building in scale 1 : 2 (Wei et al. 1991) is tested by using of pseudo-static method for evaluating the aseismic behavior for a 8-storey residence. The crack pattern at limit state is shown in Fig. 3, and the max. displacements and shear force between storeys are listed in Table 2.

The horizontal bending cracks were first occurred at the window corners of the wall on first and second storey if the cyclic horizontal load was 400kN, and as soon as the load reached to 500kN the inclined cracks appeared in the transverse walls at 4th and 5th storeys. The inclined cracks occurred in the walls at 3rd to 6th storeys where the horizontal load had been increased to 600kN. The maximum total horizontal load being the limit state was 840kN, at which one of the end confined column at 4th storey was broken in footing. The crack pattern is shown in Fig. 3. The Lateral displacement of the model building is much more like a shear type.

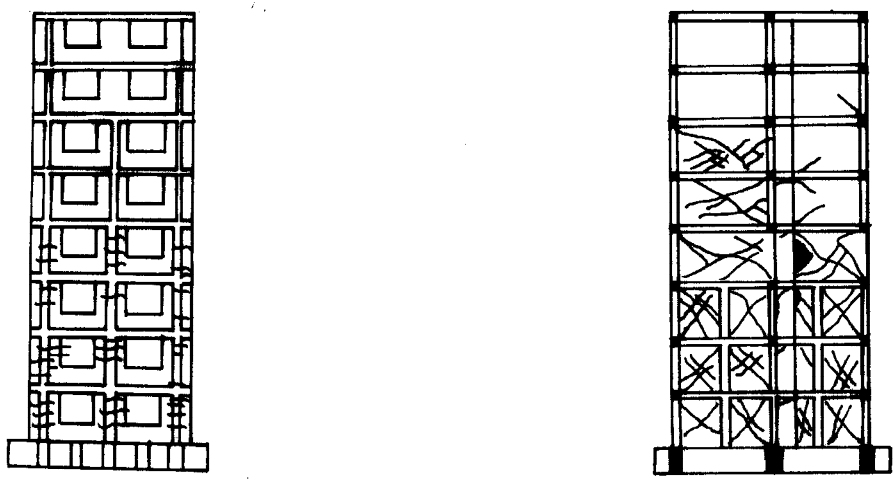

Fig. 3 Crack Pattern of 1 : 2 Model Building

Table. 2 Moderbuilding Tests

No. of Storeys	$\frac{\Delta c}{h_i}$	Q_c kN	$\frac{\Delta_{max}}{h_i}$	Q_{max} kN
1	1/700	660	1/233	840
2	1/636	660	1/165	840
3	1/560	540	1.156	756
4	1/450	450	1/108	756
5	1/519	375	1/123	588
6	1/482	420	1/208	588
7	1.964*	200	1/300	252
8	1/964*	200	1/338	252

Δc: crack storey displacement;
h_i: height of ith storey;
Δ_{max}: maximum storey disp;
* ; uncracked

The earthquake base shear force be 397kN as specified by the current 《Aseismic Structure Design Code GBJ 11—89》, if the earthquake intensity is 8. However, the test result shows that the model building still stayed in elastic state without any cracking, and the maximum storey drift ratio was 1/450 before the horizontal load reached to 400kN. That is to say the model building satisfies and fulfils all the requirements of the code.

Vertical Force Distribution Between Columns and Masonry

For both transverse and longitudinal walls, it is found that columns and masonry would resist vertical and horizontal loads as a whole structural element until failure of wall occurs.

In case of the wall is loaded only vertically, along the height of the wall from top to bottom the portion of the load sustained by columns would be increased and that by masonry decreased. At the bottom of the wall vertical load is basically distributed between the columns and masonry according to their stiffness. If there exists a horizontal load, the proportion of load distributed to columns would decrease at the limit state, but they would still make contribution to have resisted about 30% of the vertical load.

ELASTIC-PLASTIC ANALYSIS OF WALL STRENGTH

A more accurate nonlinear finite element method for evaluating strength and deformation of composite walls is hereby briefly introduced. By comparing with the test results (see Table 1), it could be concluded that this method would provide appropriate accuracy in engineering applications. By applying of this FEM to calculate a series of composite walls with different sizes of confined columns, different height to width ratios of walls and varied grades of concrete, brick/block and mortar, etc. Some simplified formulas of strength and deformation, which are being accepted and currently used in the 《Composite Masonry Wall System Building Design Code of Shenyang City (1995)》, have been established.

Basic Assumptions

The composite walls are treated as a plane stress problem and FEM is thus applied. Brick masonry is considered as a homogenous elastic body, but with different local strength in horizontal and vertical directions. Assumptions are made that there is no slip between steel reinforcements and adjacent concrete and neither the separation between columns and masonry.

By using an isoparametric rectangular element being included with reinforcement as a two-force member, computing this element stresses, according to different criteria corresponding to crushing, cracking, shear failure for mortar joint etc. to decide whether the element is at failure or not. If an element is cracked, its stiffness would decrease and its stiffness becomes zero while it is to be crushed. The part of the load at which an element at failure can hardly bear will be transfered to element nodes. Such transfered nodal forces are to be treated as external load and be redistributed in the wall. This would therfore be an iterative process for the nodal force. The failure causes and failure sequence of elements, cracking directions, limit capacity and displacements corresponding to each external load value are printed in this program.

EARTHQUAKE SIMULATING SHAKING TABLE TEST

A 1 : 4 scale 8-storey model building was tested on shaking table with input recorded EL-Centro ground acceleration. When the inputing acceleration $\ddot{x}_g$ with a peak value of 0.473g, some inclined cracks were occurred in the walls at first and second storeys. The limit state appeared at $\ddot{x}_g$ of 0.851g. At this state the base shear force was to be at maximum and the appearance of cracks from 1st to 6th storeys occurred (Fig. 4), but the stresses in the reinforcing steel of all confined columns were of no more than 1/3 to 1/2 yielding strength of steel, on the confined columns, only a few bending cracks were observed. The model building would withstand such without obvious collapse.

Due to the limited bearing capacity of the shaking table, the applied ballast was made so that the vertical stresses σ_0 in walls was only 50% of σ_0 in prototype. Approximations were being made by evaluating the response both with the full value of σ_0 and its half value respectively in dynamic analysis.

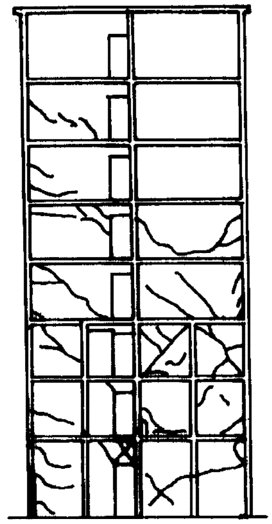

Fig. 4 Crack Pattern at Limit state

DYNAMIC ANALYSIS AND RELIABILITY

Dynamic response of a typical 8-storey composite wall building was analyzed by using of El-Centro recording. It is shown that the walls of 1st to 5th storey have been cracked by an inputing peak acceleration value of 0. 4g with a limit state value up to 0. 5g (Table 3 and Fig. 4).

Table 3 Response of Max. displacement between storey (mm)

Peak value $\ddot{x}_g$	No. of storeys							
	1	2	3	4	5	6	7	8
0. 2g	2. 38	1. 92	1. 82	2. 16	2. 32	2. 01	1. 52	0. 91
0. 4g	7. 11	5. 32	4. 45	4. 09	4. 68	3. 55	2. 79	1. 73
0. 5g	10. 03	7. 45	6. 30	5. 90	6. 14	4. 09	3. 08	1. 95
Cracking disp.	3. 91	3. 08	3. 13	4. 19	4. 26	4. 16	4. 04	4. 03
Limit disp.	10. 90	10. 90	10. 04	11. 42	11. 64	11. 62	11. 46	11. 26

Table 4 Reliability Index β to A 8-storey Building

Peak value $\ddot{x}_g$	No. of storeys							
	1	2	3	4	5	6	7	8
0. 22g	4. 8	>9	>9	>9	>9	>9	>9	>9
0. 4g	2. 7	2. 82	3. 35	4. 17	4. 18	>9	>9	

The dynamic reliability is calculated by using of the First Order Second Moment Method with displacement as criterion (Wu et al. 1981) and 20 recorded earthquake ground motions are collected to get the response sample data. The obtained reliability index β are listed in Table 4. It shows that when the peak acceleration values are of 0.22g and 0.4g corresponding to the minimum β 4.8 and 2.7 respectively.

CONCLUSIONS

If the connections between columns and masonry, columns and beams would not break away until their failure, the composite masonry wall composed of confined RC columns, beams and brick/block masonry could be treated as a single element in structural analysis.

Dynamic analysis indicates that it is applicable with appropriate reliability for a 8-storey composite masonry building in the seismic area of intensity 7 (the peak value of ground acceleration is 0.1g). If the first and second storey be strengthened, then a 8-storey composite biulding could be constructed on the seismic zone of intensity 8.

Confined RC columns in composite masonry walls are able to sustain part of the vertical load, this leads to that the wall could be made thinner.

The stiffness differences between storeys should be within the range of 30% in order to avoid deformation concentration.

REFERENCES

Wei, L. and Q. G. Zhang et al. (1991). Experimental Study on Aseismic Behavior of 8-storey Composite Wall Building. Proc. of First National Conference on Masonry Structures, Vol. II, 26—37 (in Chinese).

Wu, R. F. and H. X. Gu (1981). Aseismic Reliability of Multi-Storey Masonry Building with Constructional RC Columns. Proc. of First National Conference on Earthquake Engineering, 86—94 (in Chinese)

Wu, R. F. and H. X. Lu et al. (1982). Test and Analysis of Brick Walls With Reinforced Concrete Columns Under Lateral Cyclic Loading. Proc. of US-PRC Bilateral Workshop on Earthquake Eng., Vol. I, C—2, 1—19.

Xi, X. F. and R. F. Wu et al. (1995). Elasto-Plastic analysis and Approximate Formalas of Lateral Strength and Stiffness for Composite Walls. Earthquake Resistant Engineering, 64, 5—9 (in Chinese).