11th Canadian Masonry Symposium, Toronto, Ontario, May 31- June 3, 2009

TEST AND RESEARCH ON THE ULTIMATE BEARING CAPACITY OF THE REINFORCED CONCRETE MASONRY COLUMNS SUBJECTED TO ECCENTRIC LOAD

Pan Jing[1,2] and Liu Ming[2]

[1] School of Civil and Hydraulic Engineering, Dalian University of Technology, Dalian , China, panjing81@126.com

[2] School of Civil Engineering , Shenyang Jianzhu University, Shenyang , China, liumingsy@vip.sina.com

ABSTRACT

The experimental and theoretical analysis of reinforced concrete masonry column subjected to eccentric loads was presented. Sixteen tests of reinforced concrete masonry columns had been performed. The effect of the slenderness ratio was the principal variable considered. The slenderness ratio varied from 6 to 18, while the steel reinforcement ratio and eccentricity remained constant. The mechanic properties and failure mode were studied in this paper. With the increase of slenderness ratio, the original tangent stiffness of the specimen gradually decreases, and the ultimate load-bearing capacity declines dramatically. Based on the experimental study and theoretical analysis, modification is proposed on the design equations of compressive capacity of reinforced masonry column in design codes, which can be provided as the design basis on reinforced concrete masonry column.

KEYWORDS: column；reinforced masonry；slenderness ratio；eccentricity.

INTRODUCTION

Concrete masonry structures have been researched and applied to practice for over 40 years in China. Small concrete hollow block as a fairly mature new masonry material is becoming more widely used since its feature is in accordance with the national policy of soil saving, energy saving and together with the gradual disability of fired common brick in China[1]. Reinforced concrete masonry structure develops on the basis of unreinforced (plain) masonry structure, and it is a new structural system in China[2]. Since it has good earthquake-resistant property, the structure gets rid of the shortcoming of low intensity and bad ductility that unreinforced masonry structure has so that it can be used to construct middle-high and tall buildings[3].

At present, the design provisions of reinforced masonry column have been specified in the national code[4] in China, but the design method of the column on eccentric compression condition has not been included in the above design code, and the compression behavior and failure mechanism for it has not been studied systematically and particularly, therefore, an experimental study was conducted focusing on the effect of the slenderness ratio and eccentricity to the compression behavior of the column.

Twelve 1/3-scale and four full-scale reinforced concrete masonry column specimens were tested. Eccentric load was applied to the centroidal axis of the column. The deformation, strain, failure mode, and ultimate bearing capacity of them have been observed and analyzed.

TEST PROGRAMME

The experimental program was carried out on sixteen reinforced concrete masonry column specimens built at the laboratory of structural engineering in Shenyang JianZhu University using the same type of construction technique. The geometry and parameter of the different specimens are summarized in Table 1. In it, ZY represents full-scale specimen, and ZM represents 1/3-scale, every column group has two replicate specimens, A=column cross-section area, L= column length, β =L/d, d=least column cross-section dimension, e= eccentric distance, y= distance from the centriod of the section to the edge of the section along the eccentric direction where the axial load lies, ρ = steel reinforcement ratio. The slenderness ratio uses 6, 8, 10, 12, 16, and 18; the steel reinforcement ratio is 0.4%. The initial eccentric distance uses 0.7y , where y is the distance from the centriod of the section to the edge of the section along the eccentric direction where the axial load lies.

We uses 1/3-scale specimens to simulate the reinforced concrete masonry column and to reflect its true compression behavior, in order to achieve the tests for higher columns which with big slenderness ratio. Meanwhile it is also necessary to built some full-scale specimens for lower columns which with small slenderness ratio to make comparisons between 1/3-scale and full-scale specimens, thus we can check that if the 1/3-scale test results are reflected and reliable.

Table 1: Specimens Group Series and Geometry Parameters

Group series	A (mm×mm)	L (mm)	β	e/y	ρ %	Arrangement of steel bar
ZY-1	390×390	2390	6	0.7	0.4	Vertical bar: total= 4 Diameter=14 mm Stirrup diameter=8 mm Stirrup spacing=200mm
ZY-2	390×390	3210	8	0.7	0.4	
ZM-1	130×130	802	6	0.7	0.4	Vertical bar: total= 4 Diameter=6 mm Stirrup diameter=2.5 mm Stirrup spacing=66 mm
ZM-2	130×130	1066	8	0.7	0.4	
ZM-3	130×130	1333	10	0.7	0.4	
ZM-4	130×130	1600	12	0.7	0.4	
ZM-5	130×130	2132	16	0.7	0.4	
ZM-6	130×130	2397	18	0.7	0.4	

Figure 1 is the sketch map of the column material makeup and section form. All specimens were cured under natural condition and tested after 58 days.

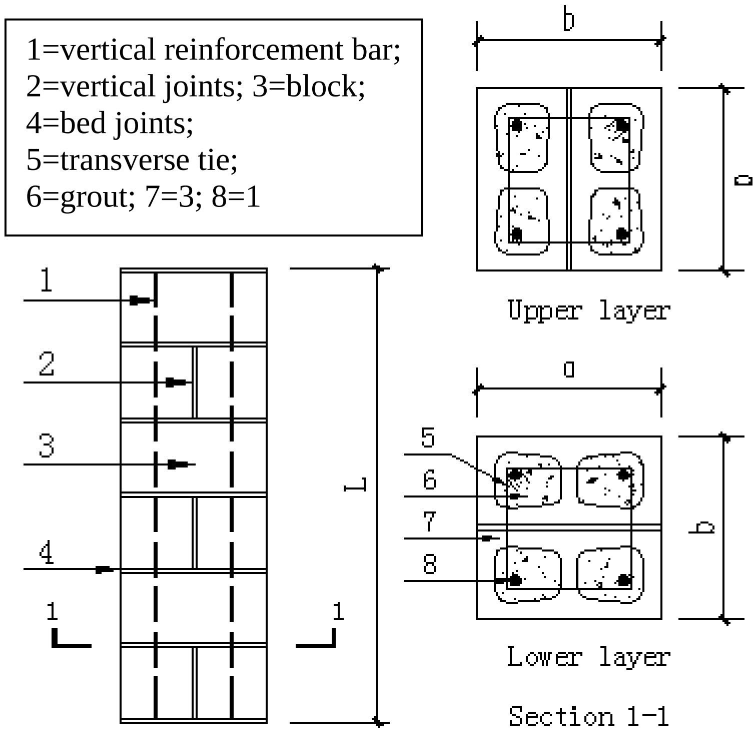


Figure 1: Schematic of Typical Column Specimen

In this test, the ungrouted CMU used. The mortar was a special mortar for concrete block consisting of 1 part type 1 grade 32.5 silicate-slag cement made in Liaoning Gongyuan cement plant, 4.40 parts common medium sand (silver sand for 1/3-scale test), 0.33 parts of a modified chemical admixture No.4 from China Northeastern Building Design Academy, and 0.78 parts water by weight. The grout consisted of 1 part type 1 grade 32.5 silicate-slag cement, 2.63 parts common medium sand (silver sand for 1/3-scale test), 3.63 parts 10 mm (3mm for 1/3-scale test) nominal maximum-size stone, 0.35 parts of a modified chemical admixture No.5 from China Northeastern Building Design Academy too, and 0.48 parts water by weight. The chemical admixture labeling No.4 was used to improve mortar strength, mobility and water retentivity and the admixure labeling No.5 was to compensate for shrinkage and enhance placability of the grout. The vertical reinforcing bar were grade HRB335 with a yield strength of 359 MPa and ultimate strength of 527 MPa. The modulus of elasticity of the bars was 208 GPa. The transverse bar used for all specimens were smooth bars of grade HRB235.

Table 2 summaries the characterizations of the materials used in this test program. The average compressive strengths of the mortar and grout were obtained respectively on mortar specimens 70.7×70.7×70.7mm and grout specimens 150×150×150mm in size after 28 days of curing.

In addition to the sixteen column specimens tested in eccentric compression, grouted concrete block masonry were fabricated and tested, as seen in Figure 2, the mean strength of the masonry (average of six test results) is summarized in Table 3.

Full-scale masonry specimen 1/3-scale masonry specimen

Figure 2: Grouted Concrete Block Masonry

Table 2: Summary of Masonry Material Test Results

Results / Material	Full-scale test		1/3-scale test	
	Specimen size (mm)	Compression strength (N/mm^2)	Specimen size (mm)	Compression strength (N/mm^2)
Mortar	70.7×70.7×70.7	17.8	70.7×70.7×70.7	16.6
Grout	150×150×150	42.7	150×150×150	35.6
Block unit	390×190×190	14.8	130×130×63.3	8.8

Table 3: Summary of Grouted Concrete Block Masonry Test Results

Results / Specimen	Specimen size (mm)	Compression strength (N/mm^2)	Average strength (N/mm^2)	COV	Test type
P-1	590×390×190	16.45	15.2	0.08	Full-scale test
P-2		13.50			
P-3		15.45			
P-4		16.60			
P-5		13.90			
P-6		16.45			
M-1	200×130×63.3	11.05	12.0	0.13	1/3-scale test
M-2		14.58			
M-3		11.06			
M-4		10.96			
M-5		13.11			
M-6		11.20			

The vertical compressive loads were supplied by a 5000 KN capacity column testing machine which is controlled by a closed-loop hydraulic loading system. The upper crosshead of the column testing machine was fitted with round-edge hinged support which, during tests, was parallel to the axis of the column. The desired eccentricity can be achieved by adjusting the location of the column. The lower end of the specimen is directly fixed on the bottom plate of the testing machine (the specimen is fairly high, so it's dangerous to equip the lower end with a hinge), and there is hinge connection between the bottom plate and the foundation of the testing machine, which rotate to meet the demand of hinged support, so that eccentric loading can be realized (Figure 3—Figure 4).

Figure 3: A Specimen Under Test

In order to validate the sections remain plane hypothesis and measure column strains accurately, five strain gauge were used on the column midheight and spaced uniformly, three gauges were used on both the compressive side and tensile side along the length of the column. Column lateral deflections were obtained by using seven displacement transducers with a maximum range of 100mm which identified the bending plane of the column. One of them was located in the column midheight, four spaced uniformly along the length of the column, and the other two were located at the top and bottom of the column respectively to ensure zero lateral deflection. A schematic view of test instrumentation is shown in Figure 4 .

Initially, the vertical normal compressive load was applied incrementally by means of the vertical hydraulic jack until the desired pre-compression load was attained and unloading to zero after checking and insuring the measuring instruments all working normally and properly. Then conducting the formal loading procedure. Stage loading and maintaining the load for a few minutes (7~8minutes), using the data acquisition system (UCAM-70A) to monitor and record displacement and strain value at the interval when the stage load applied reaching 10% of the estimate damage load. Upon reaching the 80% of the estimate damage load, the vertical load was continuous applied until the ultimate strength was reached.

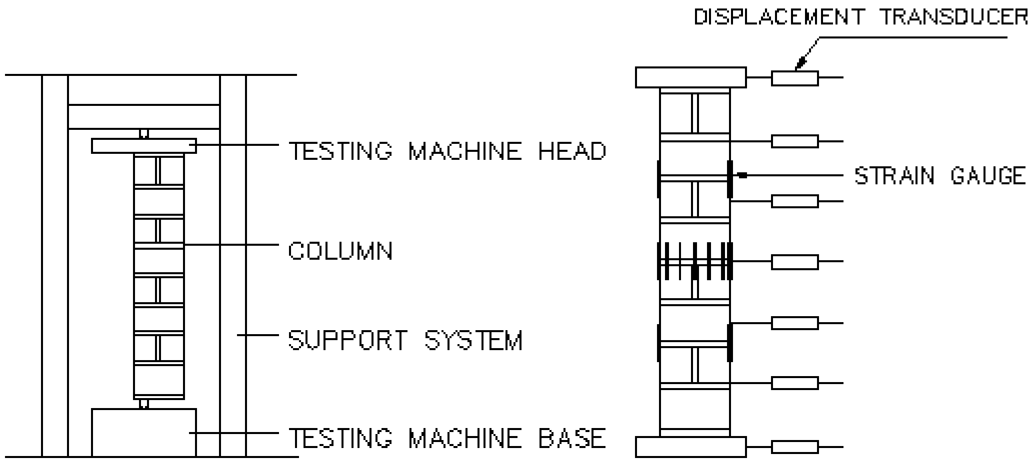


Figure 4: Testing Setup and Layout of the Surveying Point

EXPERIMENTAL TEST RESULTS

Figure 5 shows the crack and failure patterns of some representative specimens of the test. As seen in Figure 5, the failure patterns of ZM-1 and ZM-2 (1/3-scale specimens) are similar to that of ZY-1 and ZY-2 (full-scale specimens), the first cracks start to open in the middle part of the column in tensile side when the load reaches to about 30% of the maximum load and the cracks only appear in the bed joint of tensile zone, the compressive side of the column is intact. Then continuing enlarging the load, more cracks appear in the adjacent bed joints following the direction of length of the column. At the moment, because the vertical reinforcement bar in resists tension, the horizontal cracks appeared in the bed joints of tensile zone will not propagate. When the load reaches 80% ~ 90% of the damage load, typical horizontal crack can be seen in the tensile zone and vertical cracks appear in the compressive zone of the column. upon reaching the damage load, the block shells of the masonry in the compressive zone are crushed and detached from the core grout.

As the slenderness increases, all of the bed joints in the tensile side of the column are cracking before damage load arrived when slenderness increasing to 16 (ZM-5) and the deformation brought on by lateral bending is obvious and macroscopic (Figure 6). The typical horizontal crack which can be seen clearly in the tensile zone develops continually and extends to the cross-section center where the crack located following the transverse direction when damage load arrived.

When the slenderness ratio increases to 18 (ZM-6), compared to ZM-5, the typical horizontal crack has already extended through the cross-section center when damage load arrived.

ZY-1

ZY-2

ZM-1 ZM-2

ZM-5 ZM-6

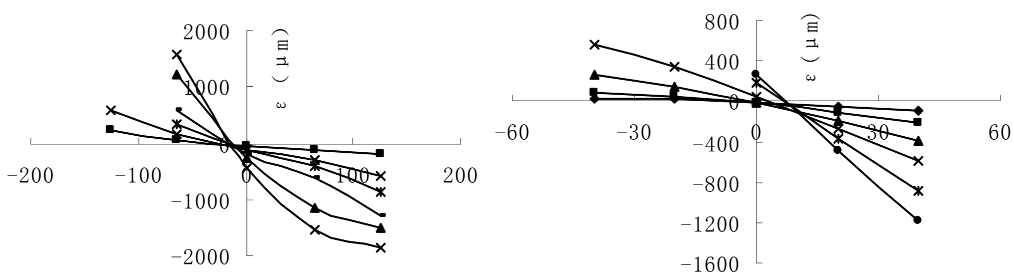
Figure 5: Experimental Phenomena

Figure 6: Photo of Lateral Bending of Column (ZM-5)

The behavior of the test specimens can be studied from the force-displacement behavior. Partial experimental column results are summarized in Table 4. In it, $f_{g,m}$ =mean testing value of concrete block masonry compression strength, f_l=lateral deflection at midheight. Figure 7 shows the testing results of masonry strain distribution at column midheight. As seen in Figure 7, the strain distribution curve is almost straight and according with the plane hypothesis.

Table 4: Partial Column Compression Test Results

Results / Specimen	$f_{g,m}$ (Mpa)	f_l (mm)	cracking load (KN)	ultimate load (KN)
ZY-1	15.2	6.3	500	1580
ZY-2	15.2	8.9	500	1500
ZM-1	12.0	6.2	55	88
ZM-2	12.0	8.6	40	78
ZM-3	12.0	—	—	66
ZM-4	12.0	11.1	32	70
ZM-5	12.0	19.2	30	66
ZM-6	12.0	27.0	20	55



Section width (ZY-1) - mm Section width (ZM-6) - mm

Figure 7: Strain Distribution at Column Midheight

Figure 8 shows the relationship between the compressive load and midheight lateral displacement of all the specimens and Figure 9 shows the slenderness ratio versus ultimate load-bearing capacity relationship curve, where N_u=the ultimate load, N/N_u=the ratio of each stage load and ultimate load in the test. As seen in Figure 8-9, as the slenderness ratio increases, the lateral displacement at column midheight increases and the load carrying capacity decreases. And the ultimate load carrying capacity declines 5％, 17％, 22％ and 35％ respectively compared with the corresponding load-bearing capacity value when the column slenderness equals to six. It also can be seen that with the increase of slenderness, the decline rate of ultimate load carrying capacity is increasing gradually.

In the initial stage of loading, curves of all specimens are linear indicating elastic behavior in Figure 8, when the load increases to 40％～50％ of the damage load, the speed of lateral displacement increase begins to accelerate seen from the curve and indicating elastic-plastic phase. When the load increases to 80％～90％ of the damage load, the curve is already nonlinear and the lateral displacement increases faster compared with the load. When damage load is achieved, the curve reaches peak point and then begins to enter into the desending level and gradually become steep as the slenderness decrease.

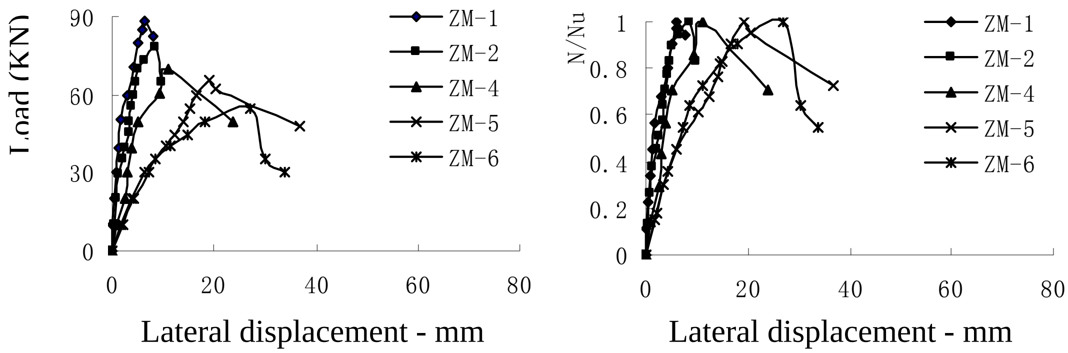


Figure 8: Load and Midheight Lateral Displacement Relationship Curve

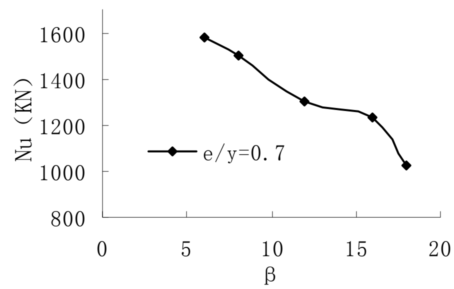


Figure 9: Slenderness Ratio versus Ultimate Load Bearing Capacity

THEORETICAL ANALYSIS

Foreign researches and common practices in China show that the mechanic properties of reinforced concrete masonry is close to that of reinforced concrete, especially in the design of load-carrying capacity of compression. Reinforced concrete masonry applies the same basic assumption that reinforced concrete uses, and this has been clearly stipulated in documents [5], [6] and[7]. Therefore, in this paper the computation formula deduction of load-carrying capacity of the reinforced concrete masonry column applies the following basic assumptions:

(1) The strain of a cross-section varies linearly;

(2) The strain of the vertical steel reinforcements should be identical with that of the adjacent masonry and grout for concrete small hollow blocks;

(3) Tensile strength without considering the masonry and grout for concrete small hollow block;

(4) Ultimate compressive strain of the masonry and grout for concrete small hollow block shall be chosen according to material and shall not be greater than 0.003;

(5) Ultimate tensile strain of reinforcement shall be chosen according to material and shall not be greater than 0.01;

(6) Adopt the masonry stress-strain curve yielded in document [8], namely $\varepsilon = -\frac{1}{\xi}\ln\left(1-\frac{\sigma}{f_m}\right)$.

We know from the test that the load carrying capacity of the column decreases as the slenderness increases because of the effect of the lateral bending which will lead to increased lateral displacement and make the column lose stability and then lose load carrying capacity rapidly and consequently, so the stability coefficient φ_0 must be considered into the formula for calculating ultimate load carrying capacity of the column. According to Euler equation [8] the critical normal stress of the column when damage accruing shall be:

$$\sigma_{\mathrm{cr}} = \frac{\pi^2 EI}{AH_0} = \pi^2 E\left(\frac{i}{H_0}\right)^2 \quad (1)$$

Where:

E =elastic modulus;

H_0=calculated height of the column.

Since the elastic modulus will decline as the compressive stress increases and will declined largely when the stress achieves the critical stress, the tangent modulus is used:

$$E' = \xi f_{\mathrm{m}}\left(1 - \frac{\sigma_{\mathrm{cr}}}{f_{\mathrm{m}}}\right) \quad (2)$$

Then the critical stress shall be:

$$\sigma_{\mathrm{cr}} = \pi^2 E'\left(\frac{i}{h_0}\right)^2 = \frac{\pi^2 \xi f_{\mathrm{m}}\left(1 - \frac{\sigma_{\mathrm{cr}}}{f_{\mathrm{m}}}\right)}{\lambda^2} \quad (3)$$

Where:

λ =the flexibility of the specimen, $\lambda = \frac{h_0}{i}$;

f_{m}=mean value of masonry compressive strength;

ξ =the elastic characteristic coefficient of masonry deformation, mainly related to mortar strength.

From Equation (3) the stability coefficient which only considered the influence of lateral bending is:

$$\varphi_0 = \frac{\sigma_{\mathrm{cr}}}{f_{\mathrm{m}}} = \frac{1}{1 + \frac{1}{\pi^2 \xi}\lambda^2} \quad (4)$$

When subjected to eccentric load, the effect of the additional eccentricity on the column stability and load carrying capacity which produced by lateral bending should also be considered. Thus, the stability coefficient φ which considered the effect of both lateral bending and additive eccentricity shall be defined by [8]:

$$\varphi = \frac{1}{1 + \left(\frac{e + e_{\mathrm{i}}}{i}\right)^2} \quad (5)$$

Where e=initial eccentricity of axial load and ei=additive eccentricity.

Introduce the boundary condition: e＝0， $\varphi = \varphi_0$, then

$$\varphi_0 = \frac{1}{1+\left(\frac{e_i}{i}\right)^2} \tag{6}$$

The additive eccentricity can be isolated from equation (6) and substitute $i = h/\sqrt{12}$ in it:

$$e_i = \frac{h}{\sqrt{12}}\sqrt{\frac{1}{\varphi_0}-1} \tag{7}$$

For reinforced concrete masonry, the real eccentricity e will be h-a, where a=the distance from the center of gravity of vertical tensile steel reinforcements to the edge of the section, when the block and core grout can not resist tensile stress any more and quit working after crack as the load increase, moreover since the steel reinforcement bears most of the tensile stress, the crack will not develop without any limit and control. Instead, it will achieve new balance under the function of rest area of the section and the reduction of eccentricity. Thus, in order to reflect the advantageous effect of vertical steel reinforced on column, a coefficient r_e is used to modify and reduce the eccentricity e.

Make: $$r_e = \frac{e-a/2}{e} \tag{8}$$

Using Equations (5) and (7) the stability coefficient formula can be defined as:

$$\varphi = \frac{1}{1+12\left[\frac{\gamma_e e}{h}+\sqrt{\frac{1}{12}\left(\frac{1}{\varphi_0}-1\right)}\right]^2} \tag{9}$$

The calculation formula of ultimate load carrying capacity is :

$$N_u = \varphi_g\left(0.8 f_g A_r + f_y' A_s'\right) \tag{10}$$

The comparison between the testing results and the results of Equation (10) is shown in Table 5. As seen in Table 5, it is clear that the results calculated using equation (10) are in good accordance with the testing results.

Table 5:Comparison Between the Calculating Results and the Testing Results of N_u Using Formula (10)

Specimen Number	e_0 / y	β	Testing Results N_u (KN)	Calculating Results N'_u (KN)	N_u / N'_u
ZY-1	0.7	6	1580	1432	1.10
ZY-2	0.7	8	1500	1387	1.08
ZM-1	0.7	6	88	83	1.06
ZM-2	0.7	8	78	77	1.01
ZM-3	0.7	10	66	71	0.93
ZM-4	0.7	12	70	66	1.06
ZM-5	0.7	16	66	57	1.16
ZM-6	0.7	18	55	53	1.04
Mean Value					1.05
C.O.V.					0.03

CONCLUSIONS

From the experimental study and theoretical analysis of the column, the following conclusions can be draw.

(1) The strain distribution curves indicate that the strain of column section was consistent plane as the compressive load increases and plane hypothesis can be used in the formula deduction of the column ultimate load carrying capacity.

(2) With the increase of slenderness, the original tangent stiffness of the specimen gradually decreases, and the ultimate bearing capacity declines dramatically. When the slenderness ratio is less than eight, the lateral displacement at midheight of the column basically keeps a linear growth and the growth rate is slow as the load is increasing. Oppositely, the lateral displacement grows more rapidly when the slenderness ratio is more than eight.

(3) Since the column is reinforced with steel, compared with nonreinforced masonry, the restrictions on the eccentricity of reinforced masonry can be relaxed as long as it meets the demand of computation, where the limit value of eccentricity is 0.6y specified in the “code for design of masonry structures” in China, although the eccentricity is one of the main factors that affects the ultimate load carrying capacity of reinforced concrete masonry column.

(4) The computation expression of ultimate load carrying capacity of the column subjected to eccentric loading is proposed in this paper, in which the influence of longitude bending and eccentricity on column is considered. The computing results coincide well with the testing results, and thus it can provide experimental data and theoretical reference for the modifying of the “Code for Design of Masonry Structures” in China.

REFERENCES

1. SHI Chuxian, (2003) “Theories and Design of Masonry Structures”, China Industry Building Press, Beijing, .
2. YUAN Zhengfang，GAO Lianyu, (2003) “New Progress on Concrete Block and Concrete Block Structures” Housing Materials & Applications, China.
3. CAI Yong, (2005) “Study on Design and Construction of a 1/4 Scale Frame Supported Reinforced Concrete Masonry Shear Walls Building”, Dphil thesis, University of Hunan, China.
4. GB 50003-2001 “Code for Design of Masonry Structures”, China Industry Building Press, Beijing,China.
5. ISO/DIS 9652-3 “Code for Design of Reinforced Masonry Structures”.
6. EN1996 “Design of Masonry Structures”.
7. ACI530-02/ASCE 5-02/TMS 402-02 “Building Code Requirements for Masonry Structures”.
8. LIU Lixin, (2001) “Masonry Structures”, Wuhan University of Technology publishing company, China.