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EXPERIMENTAL STUDY OF ULTRA-HIGH PERFORMANCE MORTAR MASONRY SHORT COLUMNS UNDER AXIAL LOADS

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Abstract

In this paper, the ultimate load carrying capacity, strain and failure modes of the ultra-high performance mortar (UHPM) masonry columns were tested and analyzed and compared with the conventional mortar (CM) masonry columns. Two kinds of different masonry material, common sintered brick and concrete block, were used for constructing test specimens. The result shows that the compressive strength of UHPM masonry column be constructed of common sintered brick is about 1.75 times higher than CM masonry columns. For the columns constructed of concrete block, the compressive strength of UHPM masonry column is increased 2.01 times. Moreover, the skeleton texture formed by UHPM was still bearing loads when the block was destroyed and also restrained the horizontal deformation to improve the ductility of masonry column as well. Therefore, it is necessary to take the effect of skeleton into consideration when it comes to ultimate load-carrying capacity and deformation calculation of the concrete UHPM short columns under axial loads.

Résumé

Dans cet article, la capacité portante maximale, la déformation et les modes de rupture de poteaux en maçonnerie de mortier à ultra-hautes performances (MUHP) ont été étudiés expérimentalement, analysés et comparés à ceux de poteaux en mortier traditionnel. Deux types de matériaux de maçonnerie, à savoir: des briques en terre cuite et des blocs de béton ont été utilisés pour la construction des corps d'épreuve. Les résultats montrent que la résistance en compression des poteaux en maçonnerie de MUHP construits avec des briques en terre cuite est 1.75 fois plus élevée que celle des poteaux en maçonnerie de mortier traditionnel. Pour les poteaux construits en blocs de béton, la résistance en compression des poteaux avec MUHP est multipliée par 2.01. De plus, le squelette constitué des liaisons en MUHP conservait une capacité portante lorsque les blocs étaient détruits et contenait la déformation horizontale, améliorant la ductilité des poteaux. Ainsi il est nécessaire de prendre en compte l'effet de ce squelette dans le calcul sous charge axiale de la capacité résistante et de la déformation ultime des poteaux courts en maçonnerie de MUHP.

1. INTRODUCTION

Unreinforced masonry has been extensively used as a construction material in the building industry, especially for residential buildings. The low shear and tensile strength of this material are the limiting properties for this adaptation. Unreinforced masonry structures are designed to withstand compressive loads and strengthening them is necessary to bear tensile forces [1-2].Sun-baked clay brick is one of the earliest basic building material used by man and indeed is still used today [3]. A great number of parameters come into play in the compressive strength of clay brick masonry walls joined together by cement mortar. In general, it can be said that the resistance mechanism of masonry subjected to compression loads depends basically on the interaction between the bricks and the mortar. The characteristics of the materials bricks and mortar also differ when they are acted upon in isolation and when they are the components of a masonry wall. It should also be borne in mind that masonry is an anisotropic element and highly sensitive to building processes. The wide range of existing parameters, some quantitative (e.g. brick compressive strength) and others more qualitative (e.g. construction process) greatly complicate the calculations and design of masonry structures [4].

Masonry structure has a long history and plays an important role in building structures. Masonry structure is widely applied, for example, over 80 % buildings in rural areas in China are constructed in masonry materials. It is necessary to repair and reinforcement the existing masonry structure for the reason that they are in failing safety or functional degradation, those demolition may cause resource waste and serious environment pollution. The results show that the factors affecting the compressive strength of masonry are: block, mortar, construction quality, size effect and confinement effect, etc. [5]. The cracks are appeared and developed along the joints, or the principal tensile stress or compressive stress [6-7].

The conventional mortar (CM) has poor durability, low strength and easy weathering, which leads to poor seismic performance of masonry structure. It is necessary to study the weak link of masonry mortar, so it is very meaningful to improve the mechanical properties of masonry structure. As a new kind of cement-based material with super high strength and high durability, Ultra-high performance mortar (UHPM) has a good application prospect [8].Steel fiber can effectively improve the tensile performance of UHPM, which can be limit the deformation of masonry pointing, and then improve the ultimate bearing capacity of masonry structure. In addition, the UHPM can withstand a variety of harsh conditions and to resist weathering's for its own high durability, which can enhance the integrity of structure. Based on this, CM and UHPM were used to carry out the axial compression test of common sintered brick and concrete block masonry column. This paper mainly studies the effect of UHPM on the compressive capacity and failure mode of the masonry short column, and discusses the feasibility and prospect of the application of UHPM in masonry structure.

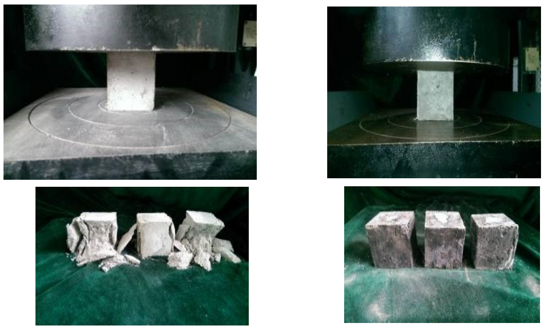
2. TEST MATERIAL

2.1 Compressive strength test of mortar

The test adopts the ordinary Portland cement with P.O.42.5, super plasticizer for poly carboxylic acid water reducing agent with water reducing rate for 25~30 %, fine sand diameter less than or equal to 0.65 mm (river sand), copper micro steel fiber with 0.22 mm diameter, 13 mm length, 2200~2350 MPa tensile strength, silica fume with average particle size about 0.1 μm and second grade fly ash. There are two groups of tests of mortar due to two types of masonry short columns. The compressive strength of CM and UHPM in common sintered brick short columns are respectively 10.9 MPa and 104.9 MPa, and concrete block short columns are 16.0 MPa and 159.9 MPa (each group has 6 specimens with size of 70.7×70.7×70.7mm). Calculation of compressive strength of mortar is strictly accordance with the *JGJ/T70-2009*. Here, the test of common sintered brick short columns is Test1and concrete block short columns is Test2. The process of test is showed in Fig.1, 2. The compressive strength of mortar cube specimen is accurate within 0.1 MPa.

（a) CM of Test1　(b) UHPM of Test1

Fig. 1: Test1: compressive strength of mortar



（c）CM of Test2　（d）UHPM of Test2

Fig. 2: Test2: compressive strength of mortar

Table 2 Compressive strength of mortar: Test1 and Test2

Type mortar	compressive strength of CM (MPa)	compressive strength of UHPM (MPa)
Test1	10.9	104.9
Test2	16.0	159.9

2.2 Compressive strength test of brick and block

Two kinds of different masonry material, common sintered brick and concrete block, were used for constructing test specimens. The size of sintered brick and concrete block is both 240 mm × 115 mm × 53 mm. The designed compressive strength of them is respectively 10 MPa and 25 MPa. Each group has 10 specimens. Compressive strength brick and block are calculated according to *GB/T5101-2003* and *GB/T2542-2012-7.6.1*. The test specimens are showed in the following Fig. 3, and calculated data in Table 3.

(a) Compr. test of common sintered brick　（b）Compr. Test of concrete block

Table 3 Compressive strength of common sintered brick and concrete block

Type brick	compressive strength (MPa)
common sintered brick	7.78
concrete block	24.1

3. MASONRY SHORT COLUMNS UNDER AXIAL LOADS

3.1 Preparation

It should be recorded when specimens is bumped and bruised and abandoned when they are severely damaged in inspecting. On the four sides, the vertical and horizontal marks should be made. And the thickness and width are measured respectively in the position of 1/4, 1/2, 3/4 (See Table.4). And height should be measured from the below plate pad to the top one. The accuracy is controlled within 1mm. Height of specimens should be from the top surface of the below pad plate (as the base) to the top surface leveling and accurate to 1mm. Displacement and strain gauges are not arranged for the common sintered brick short column is used to observe the failure mode and bearing capacity. The specimen model is shown (Fig. 4). In order to test the relationship between load and vertical and horizontal displacement curve, the vertical displacement meter is arranged on the pressure plate and the horizontal displacement meter is arranged along the height of specimen (1/4H, 1/2H, 3/4H). The transverse and longitudinal concrete strain gauges are arranged in the middle part of the specimens to measure the horizontal strain and the vertical strain (Fig. 5).

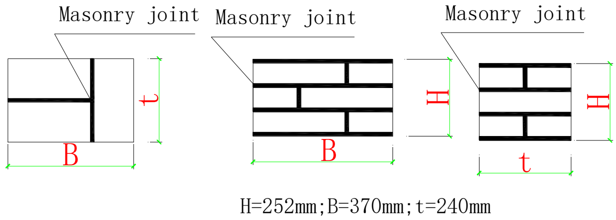


Fig. 4: Specimen model of common brick masonry short columns

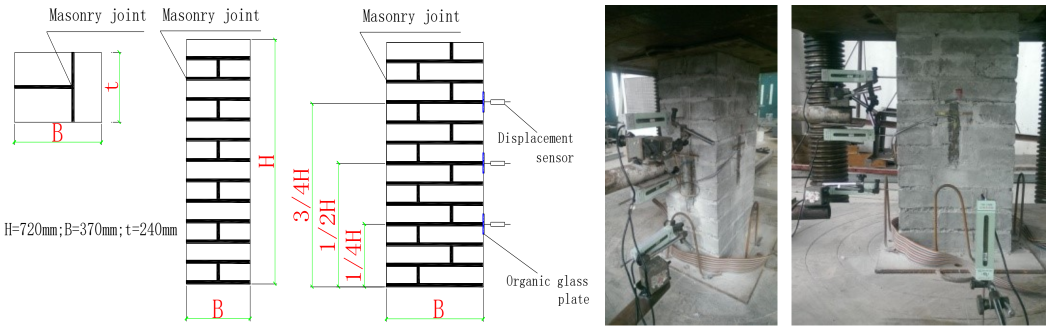


Fig. 5: Specimen model of concrete block masonry short columns

Before testing, the flatness and cleaning of steel plate should be checked. If necessary, using mortar to ensure the flatness of the specimens. A piece of steel plate is placed at the top of the specimen to avoid the local compression. Before testing, the specimens were preloaded for 2~3 times with 10~20% of the ultimate load. There are two load system, force control and displacement control. In the early stage, the force control is applied with force rate of 0.2~0.5 kN/min, and in the late stage, the displacement control is applied with the speed of 0.1~0.2 mm/min. In the course of the experiment, the appearance, development and special situations of the cracks were observed in time, and the corresponding load values were recorded. The calculation of masonry short column axial bearing capacity is accordance to the GB 5003-2001, see equation (1):

$$f_m = k_1 f_1^{\alpha}(1+0.07f_2)k_2 \tag{1}$$

where: f_m is the average compressive strength of masonry structure, MPa; f_1 is the average compressive strength of block, MPa; f_2 is the average compressive strength of mortar, MPa;

k_1 and α are parameters related to the block type and masonry category, for common sintered brick, $k_1 = 0.78$, $\alpha = 0.5$; and for concrete block, $k_1 = 0.46$, $\alpha = 0.9$.

3.2 Test of common brick masonry short columns

The size of common brick masonry short columns is shown in Fig. 4. The whole test process of concrete masonry short column is roughly same to the common brick masonry short columns, both of them can be divided into three stages: the stage before cracking and working with cracks and the cracks extension to the failure. According to the test results, the initial cracking load of the CM is about 44.5 %~47.2 % of the ultimate load-carrying capacity, while the UHPC is 45.5 %~77.3 %. It deserves noting that the failure of CM specimens is brittle failure, and the UHPM specimens is combined with semi brittle and semi ductile failure and the cracking would be delayed. Typical figures are shown in (Fig. 6).

(a) Failure mode of CM masonry columns

(b) Failure mode of UHPM masonry columns

Fig. 6: Failure mode of masonry columns

The ultimate bearing capacity of CM and UHPM for the same batch of common sintered brick masonry short columns is respectively 806.14 kN and 1412.01 kN (See Table 4). It shows ultimate bearing capacity increased by 1.75 times. There are basically two reasons to improve the ultimate bearing capacity. Firstly, the compressive strength of UHPM is relatively high and its skeleton is capable of bearing the load when the block is destroyed; secondly, the better bond performance and smaller transverse deformation in compression of UHPM improves the integrity of the short column. By comparing the experimental results with the calculated values, it is found that the calculated values are larger than the average value of the test. This paper will not discuss the correctness of code due to the limited number of specimens. But UHPM's improvement in compressive capacity of short columns is obvious.

The relation between crack development and the load in the test of short columns is also divided into three stages [9]. First, the cracking is related to the load and continues to expand with the increasing load. Then, the crack development has no relation with the increasing load. With unchanged load, the cracking keeps expanding to form a main crack in a short time. Finally, the instantaneous load value will fall when the load control is changed into the displacement and then the load will increase with the raise of displacement until the specimen is destroyed. Although crack development is basically the same, UHPM will relatively delay the appearance of initial crack and brick crack develops fully in the later stage. Observing the influence of UHPM on the failure form and the bearing capacity of the common sintered brick masonry short column lays the foundation of concrete masonry short columns test.

Table 4 Bearing capacity test results of common sintered brick masonry short columns

Specimens Number	Size（mm^2）	Failure load N_u (kN)	Crack load N_{cr} (kN)	N_{cr} / N_u	Ultimate stress（MPa）	Eq. 1（MPa）
CM-1	232*327	739.0			9.74	
CM-2	230*330	847.06	400	0.472	11.16	3.84
CM-3	233*328	832.34	370	0.445	10.89	
Average value		**806.13**			**10.60**	
UHPM-1	232*333	1539.00	700	0.455	19.92	
UHPM-2	229*329	1202.43	930	0.773	15.96	24.33
UHPM-3	231*332	1494.60	1100	0.736	19.49	
Average value		**1412.01**			**18.46**	

3.3 Test of concrete masonry short columns

3.3.1 Test procedure of concrete masonry short columns

The size of concrete block masonry short columns is shown in Fig. 5. The whole test process of concrete masonry short column is roughly same to the common brick masonry short columns, both of them can be divided into three stages: the stage before cracking and working with cracks and the cracks extension to the failure. For CM concrete block masonry short columns, the cracks are basically carried out along and concentrated in the joints, so the strength of the block is not fully utilized. In contrast, cracks of UHPM concrete block masonry short columns are more fully carried out due to high compressive strength of UHPM as well as make the block strength to be fully utilized.

(a) Failure mode of CM masonry **short** column　　(b) Failure mode of UHPM masonry short column

Fig. 7: Failure mode of masonry short columns

It is worth noting that the CM specimen is damaged by brittle failure, while the UHPM specimen has greater deformation, thus is tending to semi-brittle semi-ductile damage. Typical crack photographs are shown in Figures 7(a), 7(b).

3.3.2 Bearing capacity of concrete masonry short columns

The ultimate bearing capacity of CM and UHPM for the same batch of common sintered brick masonry short columns is respectively 1335.48 kN and 2725.64 kN (See Table 5). It shows ultimate bearing capacity increased by 2.04 times. There are basically two reasons to improve the ultimate bearing capacity. Firstly, the compressive strength of UHPM is relatively high and its skeleton is capable of bearing the load when the block is destroyed. Secondly, the better bond performance and smaller transverse deformation in compression of UHPM improves the integrity of the short column.

Table 5 Results of bearing capacity of concrete masonry short columns

Specimens Number	Size（mm²）	Failure load N_u (kN)	Crack load N_{cr} (kN)	N_{cr} / N_u (%)	Ultimate stress σ_u（MPa）	Eq. 1（MPa）
CM-1	366*240	1426.07	700~750	49.1~52.6	16.23	17.10
CM-2	366*240	1231.00	700~750	56.9~60.9	14.07	
CM-3	365*240	1349.38	750~800	55.6~59.3	15.00	
Average value		**1335.48**			15.10	
UHPM-1	368*240	2718.91	1750~1800	64.4~66.2	30.77	
UHPM-2	370*240	2600.00	1800~1850	67.3~69.2	28.27	
UHPM-3	368*240	2858.19	1800~1850	63.0~64.7	32.12	
Average value		**2725.64**			**30.39**	

By comparing the experimental results with the calculated values, it is found that the calculated values are larger than the average value of the test. This paper will not discussed the correctness of code due to the limited number of specimens. But UHPM's improvement in compressive capacity of short columns is obvious.

The relation between crack development and the load in the process of short columns is also divided into three stages [10]. At first, the cracking is related to the load and continues to expand with the increasing load. In second stage, the crack development has no relation with the increasing load. With unchanged load, the cracking keeps expanding to form a main crack in a short time. Finally, the instantaneous load value will fall when the load control is changed into the displacement and then the load will increase with the raise of displacement until the specimen is destroyed.

Although crack development is basically the same, UHPM will relatively delay the appearance of initial crack and brick crack develops fully in the later stage. The integrity of the UHPM specimen is better and the lateral deformation is smaller after it reaches the ultimate bearing capacity. This may be related to the high adhesion between the UHPM and the block, which may limit the lateral deformation of the block body. In addition, the mortar frame can also bear the axial load after the block is damaged

3.3.3 Deformation properties of concrete masonry short columns

The trend of load-displacement curve of the two mortar masonry short column is roughly the same in early stages. The load of UHPM is obviously increased when the vertical displacement is ≥ 25 mm, that is, the effect of UHPM in improving the compressive load is more significant (See Figure 8a), however, the horizontal deformation is smaller and negligible compared to the vertical deformation (See Figure 8b).

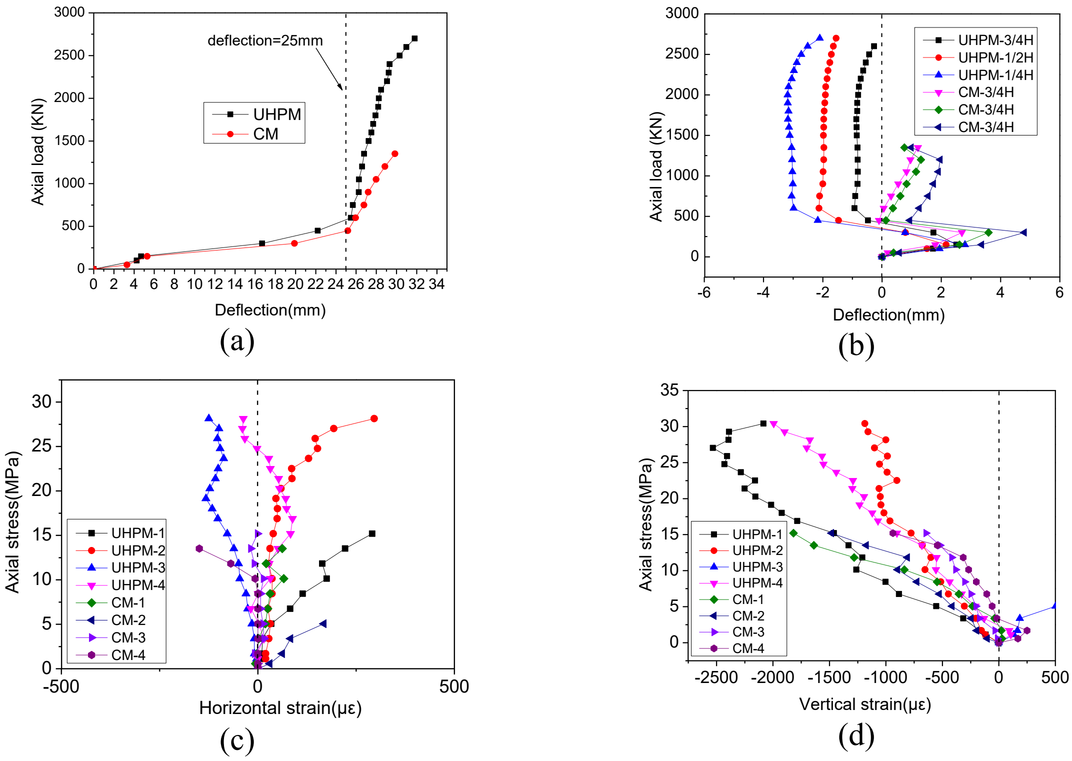


Fig. 8 (a): Load and vertical displacement curve; (b): load and horizontal displacement curve; (c): Stress and horizontal strain curve; (d): stress and vertical strain curve

A short-term "mutations" of horizontal deformation happened in the mid-term is slightly linear along the height and the horizontal deformation is basically around the y-axis. From the two kinds of short-column stress-strain curve we learn that the horizontal strain is smaller compared to the vertical strain under the same load. Under the circumstance of using UHPM, the vertical deformation capacity of the masonry short columns will increase, especially in the middle and later stage (See Figures 8c, 8d).

3.3.4 Reasons of the higher bearing capacity of the UHPM

Based on the above analysis, the ultimate load carrying capacity of UHPM-MC is obviously higher than that of CM-MC, and the lateral deformation of the former is higher than that of the latter. The reason may be:

(1) The shearing and bending strength of block is much lower than the compressive strength. Due to the uneven surface of the block and mortar pavement, blocks are not evenly pressured but affected by shearing and bending at the same time. Thus in the test of UHPM-MC and CM-MC, the first cracks appears in single brick for the reason that it cannot withstand the bending and shearing stress. The crack in CM is developed along the joint, while the situation of UHPM is totally different. The steel fiber in UHPM prevents the quick destroy of masonry after the appearance of single brick and its extension to the joints and the cracks will not develop until the steel fibers are pulled out of the mortar, which leads to the full utilization of compressive capacity of the blocks without cracks

(2) The lateral deformation will be produced when the blocks is under the vertical pressure. According to the experimental data in the references [11], it is found that the elastic modulus of mortar can be expressed by the compressive strength of mortar. The average elasticity modulus of CM is 10.87 GPa. The elastic modulus of the concrete block adopts 30.00 GPa according to GB50010-2010. Elastic modulus of CM is smaller than the block, leading to the situation that lateral deformation is larger than the block under the same load. Furthermore, the cementing bond exists between block and mortar, the two have a common deformation. Therefore, the block is subjected to tensile stress to prevent the deformation of the mortar and mortar is subjected to compressive stress. The elastic modulus of UHPM in this experiment is 39 GPa. The situation is contrary to the CM, that is, the block is subjected to the compressive stress, and the UHPM is subjected to the tensile stress. And the tensile strength of the UHPM with steel fiber is almost equal to the compressive strength the block, thus it can take full advantage of the compressive capacity of the block. Moreover UHPM can play a role of skeleton, that is, it can still bear the vertical load after the broken of block.

4 CONCLUSIONS

The conclusions are drawn by experimental study of UHPM masonry short columns under axial loads:

- The failure mode of the brick masonry short column with UHPM is similar to that of the CM. The first crack starts in single brick, and masonry short column is divided into several independent pillars with the development of the cracks in the final stage.
- The ultimate load-carrying capacity of the UHPM masonry short columns is obviously higher than that of the CM. For the same batch of common sintered brick masonry short columns, the UHPM is increased by 1.75 times. For the same batch of concrete block masonry short columns, the average compressive strength reaches to 30.39 MPa, which is 2.01 times of CM, and 1.26 times of concrete blocks when the UHPM skeleton effect is considered. Although the UHPM is quite expensive, comprehensively considering the durability of structural performance in-service life, the maintenance and reinforcement costs are low.
- Preliminary, the pre-experiment was carried out by using the ordinary sintered brick remaining in the building, and the results of the ultimate load-carrying capacity test and failure mode observation were in line with the expectation. The concrete block short column test also verified the feasibility of UHPM in masonry structure. In the later stage, the basic mechanical properties of UHPM and its application in seismic strengthening of masonry structures will be further discussed.

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