A Research on Space Work of Multistory Brick Masonry Building

Liu Ji, Wang Huanding, Li Xuan, Zhang Ying*

Summary

Through field measuring of multistory brick meaonry buildings and systematic testing of an experimental building in all processes of construction, this paper reveals the space work behaviour of multistory building under wind load and proposes a theory of multifactors of space action for multistory building analysis. With these factors, the analysis of a multistory building with consideration of space action can be done as in a plane system.

1 Introduction

At present, the design of multistory brick masonry building is controled within a "rigid scheme" with short distance between transverse walls. In order to meet the requirement for larger interiorspace inside buildings, it's desirable to increase the distance between transverse walls. But because the convertional design method, which does not consider space action of building and deal with the building as "plane frame", can not reflect the actual behavior of the building, the building with increase distance between transverse walls would seen not safe enough.

Making use of the data obtained through field measuring of 10 multistory brick massonry building and systematic testing of an experimental building in

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all processes of constuction, this paper reveals the space work behavior of multistory building and proposes a theory of multi-factors of space action for multistory building analysis.

Through field measuring, systematic test, theoretical analysis and the construction and service conditions of the experimental building, it has been proved that multistory brick masonry building with larger distance between transverse walls can also be quite safe

2. The Space Work Behaviour of Multistory Building and Multi-factors of Space Action

A great deal of research work on space action of single-story buildings has been done by scholars in many countries [1]—[6] .

From the view point of engineering design it is not only reasonable but also convenient to determine and estimate the space action of a single-story building, using a value of space action factor m. This space action factor m can be defined as the ratio of space displacement Δ_s to plane displacement Δ_p .

$$m = \frac{\Delta_s}{\Delta_p} \tag{1}$$

where Δ_s - lateral displacement at the top of the wall (or column) of the most disadvantageour bay of a building under the action of a lateral load p.

Δ_p - lateral displacement at the column top of a single plane frame under the same lateral load p.

Various values of space action factor m for single-story buildings with different distances between transverse walls and different types of roofs are provided in the Chinese Masonry Structure Design Code (GBJ3-73) .

From the view point of engineering design, how to determine and estimate the space action of a multistory building is still a problem which is worth dealing with.

The field measuring reveals clearly that when a lateral force is applied to the lower storey, the desplacement of this storey is greater than that of the upper storey. The upper storey gives such a great reaction that was not

expected before our field measuring, This fact shows that the interaction among the storeys is very strong and the space work behaviour of a multistory building is different from that of a single-story building. In a single-story building, there exists only space interaction among the bays along the longitudinal direction. In a multistory building, there are space interactions both among the bays and among the storeys. Therefore, in order to determine and estimate the space action of a multistory building, we can not use a single factor m as in case of single-story building and we must use a number of space action factors which can not be simply difined as the ratio of space displacement $_s$ to the plane displacement $_p$.

As Pointed out in papers 8 and 11, when a lateral load is applied to one of the bays of a multistory building, e.g, a two-story building as shown in Fig(1-a), the analysis of the internal forces with consideration of space action can be made as the superposition of the following two steps. In the first step, we take the plane unit (plane frame) under the direct application of the lateral load and provide a horizontal supports at each of the storey levels. Under the lateral load, the supports exert reactions R_1 and R_2(Fig 1-b). In the second step, reverse the direction of reaction R_1 and R_2 and apply them to the space system of the building (Fig 1-c). The loads distributed by R_1 and R_2 to the calculated plane until can be divided into two groups, as shown in Fig 2. They produce when the space system of the building is subjected to R_1 and R_2 respectively. The load state of the calculated plane unit is shown in Fig (2-a) and Fig (2-b), where Q_{11} and Q_{12} are the total shears in the floor to the left and right of the calculated plane unit, while Q_{22} and Q_{21} are the total shears in the roof to the left and right of the calculated plane unit.

From Fig 1 and Fig 2 we know

$$m_{11}=1-\frac{Q_{11}}{R_1} \qquad (2)$$

$$|m_{21}|=Q_{21}/R_1;\ m_{21}=-|m_{21}| \qquad (3)$$

$$m_{22}=1-\frac{Q_{22}}{R_2} \qquad (4)$$

$$|m_{12}|=Q_{12}/R_2;\ m_{12}=-|m_{12}| \qquad (5)$$

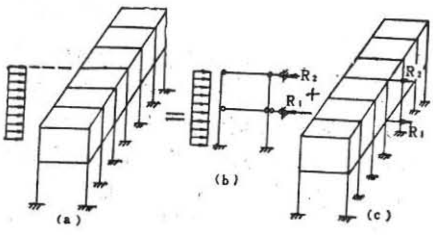


Fig 1

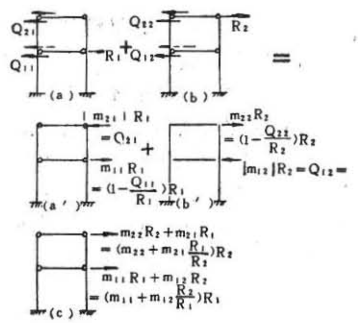


Fig 2

Under the simultaneous application of R_1 and R_2 the load state of the calculated plane unit is shown in Fig (2-c). Summing up the internal forces obtained in both steps, as shown in Fig (1-b) and Fig (2-c) respectively, we get the total internal force of the calculated plane unit, with consideration of the space action of the building, Factors m_{11} , m_{12}, m_{21} & m_{22} are called space action factors, each of them is less than 1. We call m_{11} and m_{22} the main factors of space action, while m_{21} and m_{12} the secondary factors of space action which are due to the interaction among the sotoreys. These factors have very clear physical meanings, i.e, m_{11} and m_{21} are the loads distributed the first and second storeys of the calculated plane unit when a unit force ($R_1 = 1$) is applied to the first floor of the building, while m_{22} and m_{12} are the loads distributed to the second and first storeys of the calculated plane unit when a unit force ($R_2=1$) is applied to the roof.

For a building with n storeys, there are n main factors of space action and n(n-1) secondary factors of space action and there are n^2 factors of space action in total. According to the analysis we have given in papers [8] and [11], these factors are

$$m_{ij} = \sum_{k=1}^{n} \bar{r}_{ik} \delta_{kj,s} = [\bar{r}_i]\{\delta_{js}\} \qquad (6)$$

where $[\bar{r}_i]$ -- a reaction factor row matrix of the plane unit under consideration.

$\{\delta_{js}\}$ -- a column matrix of space displacement factors.

All the main factors of space action are positive, while the secondary factors of space action may be positive or negative, but usually, $m_{i(i-1)}$ and $m_{(i-1)i}$ are negative.

3. Field Measuring of the Multistory Masonry Buildings and Systematic Testing on the Experimental Building

(1) Field measuring of the multistory masonry buildings

We have carried out field measuring of 10 two-story buildings and one three-story building. A horizontal force was applied respactively to each of the floors (including the roof) of the central bay of the building and the horizontal displacements at storey levels of each bay were measured. In order not to make this article too lengthy, here in Fig 3 the results obtained only in two buildings are given. All the data of field measuring can be found in papers 8 and 10 .

The methods of field measuring are given in papers 8 and 12 .

Put the values of space displacements of the central bay 11s. 21s, 12s and 22s recorded from field measuring into Eq (6) and the factors thus obtained are space action factors under concentrated load and marked as $m_{11c}, m_{12c}, m_{21c}, m_{22c}$. as we know, wind load is an uniform distributed load along the longitudinal

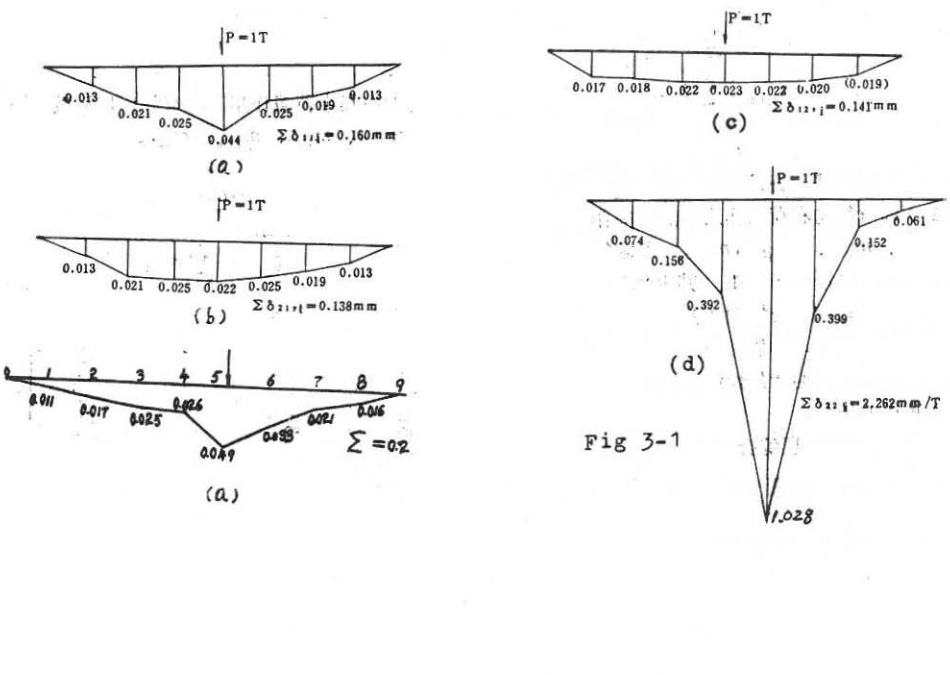
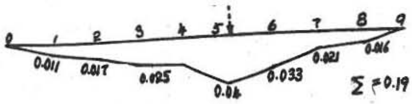
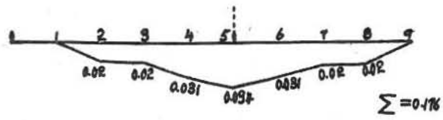


Fig 3-1



(b)



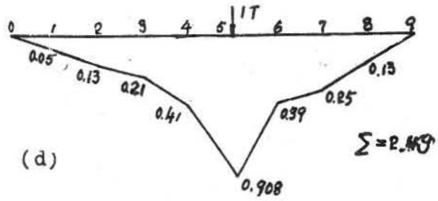
(c)

(a) measuring of the 1st story when the load is applied to the 1st story

(b) measuring of the 2nd story when the load is applied to the 1st story

(c) measuring of the 1st story when the load is applied to the 2nd story

(d) measuring of the 2nd story when the load is applied to the 2nd story



(d)

Fig 3-2

direction. In case of uniform distributed load the space displacement factors in E_q (6) will be the displacement of the calculated plane unit under an unit uniform distributed load along the longitudinal direction. It is very difficult to apply an uniform distributed load to the building during field measuring. So we just make use of the results obtained from measurements under concentrated load and calculate the space displacements of the central bay under unit uniform distributed load, basing on of the principle of superposition and the reciprocal theorem of displacemant.

$$\delta_{kjs,u} = \sum_{i=1}^{n} \delta_{jks,i} \qquad (7)$$

where i - series number of the bay.

N - total number of the bays.

Puting the results of E_q (7) into E_q (6), we will obtain the space action factors under uniform distributed load $m_{11,u}$, $m_{21,u}$, $m_{12,u}$ and $m_{22,u}$. All the space action factors obtained from field measuring are listed in table I, where ${}^{o}m_{ij}$ and ${}_{*}m_{ij}$ are results calculated from the assumption that the external walls and the girders are higned or elastically connected respectively, while m_1 and m_2 are the combined factors of space action

$$m_i = m_{ii} + \frac{R_j}{R_i} m_{ij} \qquad (8)$$

where $i=1,2$, $j=1,2$.

Table I

Factors / Buildings	$^{\circ}_{*}m_{11c}$	$^{\circ}_{*}m_{21c}$	$^{\circ}_{*}m_{12c}$	$^{\circ}_{*}m_{22c}$	$^{\circ}_{*}m_{11u}$	$^{\circ}_{*}m_{21u}$	$^{\circ}_{*}m_{12u}$	$^{\circ}_{*}m_{22u}$	$^{\circ}_{*}m_{1}$	$^{\circ}_{*}m_{2}$
I	0.015	-0.0049	-0.023	0.023	0.119	-0.025	-0.174	0.123	0.069	0.066
	0.017	-0.0043	-0.012	0.005	0.094	-0.023	-0.053	0.028	0.072	-0.034
II	0.015	-0.006	-0.077	0.063	0.038	-0.016	-0.217	0.181	-0.022	0.122
	0.013	-0.004	-0.041	0.021	0.030	-0.010	-0.116	0.060	-0.008	0.039
III	0.029	-0.009	-0.351	0.282	0.083	-0.019	-0.709	0.587	-0.126	0.521
	0.020	-0.007	-0.194	0.098	0.061	-0.019	-0.366	0.196	-0.077	0.224
IV	0.013	-0.003	-0.018	0.046	0.038	-0.007	-0.065	0.073	0.021	0.050
	0.012	-0.003	-0.008	0.006	0.035	-0.009	-0.032	0.023	0.035	-0.029
V	0.017	-0.007	-0.330	0.269	0.061	-0.023	-0.853	0.708	-0.165	0.621
	0.014	-0.006	-0.167	0.087	0.054	-0.022	-0.429	0.223	-0.069	0.160
VI	0.009	-0.002	-0.138	0.063	0.046	-0.015	-0.345	0.162	-0.057	0.157

(2) Systematic Testing on the Experimental Building

We designed a two-story experimental building in Zhen Jiang using the analysis method mentioned above and carried out systematic testing on it in different stages of construction.

That building is 48 meter long, its lateral span is 10 meters, The floor is built of prefabricated hollow plats with a layer of 3.5cm thick concrete casted in place on it. The arched truss of the building was casted in site. The roof is built of flanged plats with flat tiles on them.

As shown in papers [8] and [11], in view of the fact that the secondary factor m_{21} is quit small, while m_{12} is big, and also in order to get to the safe side the combined factor of space action of the top story is taken equal to 0.55, which is the value of space action factor m for the single-story

building as given in GBJ3-73 , while the combined space factor of the first storey m_1 equal to one fourth of the value of factor m, i.e, 0.138.

We carried out systematic testing on the building in 9 stages as the construction went on. The procedure and results are given in paper 9. Here in this paper we list only part of the testing results in Fig 4, in which the experimental curve shows the results when the applied horizontal load is equal to 1 ton.

1) the displacement of the top of the single external wall of the first storey (see Fig 4-1).

2) the displacement of the first storey as a single-storey building (see Fig 4-2).

3) the displacement of the two storey building (see Fig 4-3).

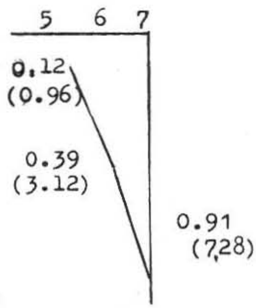


Fig 4-1

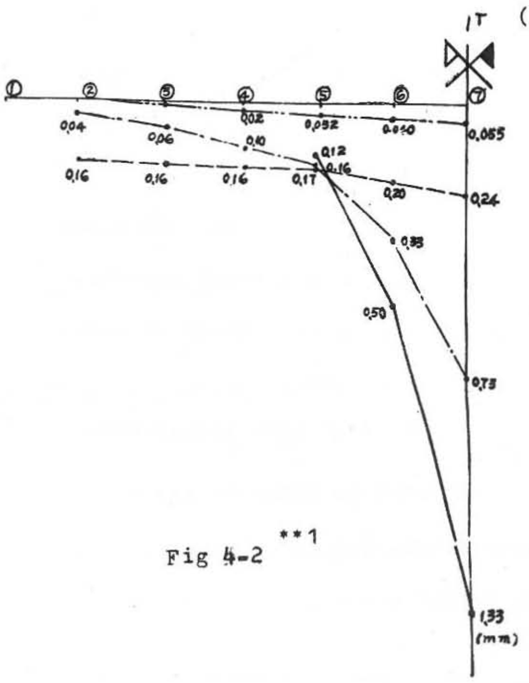


Fig 4-2 **1

**1 (a) after the girders having been put in position.

(b) after the floor plates having been set up.

(c) after the layer of concrete having been casted on the floor plates.

(d) after the temporary gables having been built at a distance

of 40 meters long.

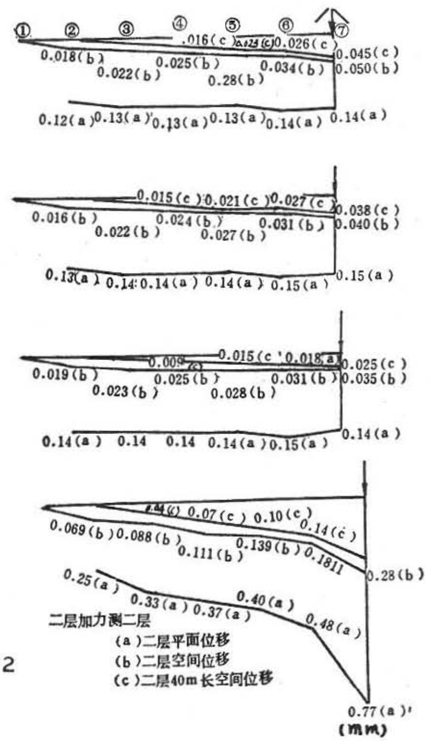


Fig 4-3 **2

**2 (1) measuring the 1st story when the load apply to 1st story

(2) measuring the 2nd story when the load apply to 1st story

(3) measuring the 1st story when the load apply to the 2nd story

(4) measuring the 2nd story when the load apply to the 2nd story

(a) displacement without gable

(b) displacement with gables (at a distance of 48 meters)

(c) displacement with temporary gables (at a distance of 40 meters)

Because we have obtained the displacement factors of the plane system without the gable, we can calculate the reaction factors of the plane system,

$$\left.\begin{aligned}\bar{\gamma}_{11}&=\frac{\bar{\delta}_{22}}{\bar{\delta}_{11}\bar{\delta}_{22}-\bar{\delta}_{12}^{2}}\\ \bar{\gamma}_{22}&=\frac{\bar{\delta}_{11}}{\bar{\delta}_{11}\bar{\delta}_{22}-\bar{\delta}_{12}^{2}}\\ \bar{\gamma}_{12}=\bar{\gamma}_{21}&=-\frac{\bar{\delta}_{12}}{\bar{\delta}_{11}\bar{\delta}_{22}-\bar{\delta}_{12}^{2}}\end{aligned}\right\} \quad (9)$$

where $\bar{\delta}_{11}$, $\bar{\delta}_{11}$, $\bar{\delta}_{12}=\bar{\delta}_{21}$ are displacement factors of the plane system, which can be obtained from the data measured without the gable. From the displacement curve in Fig 4-3, we can find $\bar{\delta}_{11}=0.160$ cm/T, $\bar{\delta}_{22}=0.463$ cm/T, $\bar{\delta}_{12}=0.173$cm/T, $\bar{\delta}_{21}=0.178$cm/t. The difference between $\bar{\delta}_{12}$ and $\bar{\delta}_{21}$ is very small, so we take their average $\bar{\delta}_{12}=\bar{\delta}_{21}$ =0.176cm/T. Substituting these values into $E_q(9)$, we obtain $\bar{r}_{11}$ =10.67T/cm, $\bar{r}_{22}$=3.697T/cm, $\bar{r}_{12}=\bar{r}_{21}$ =-4.05T/cm. Put into $E_q(6)$ all

the reaction factors and the space displacement factors, we obtain the actual factors of space action, as listed in Table II.

Table II.

factors / State of building		m_{11c}	m_{21c}	m_{22c}	m_{12c}	m_{11u}	m_{21u}	m_{22u}	m_{12u}	m_{1u}	m_{2u}
1	48M long with gables	0.0372	-0.0055	0.0892	-0.0761	0.211	-0.018	0.422	-0.286	0.062	0.380
2	40 M long with temporary gables	0.0343	-0.0056	0.0733	-0.0622	0.145	-0.0273	0.279	-0.208	0.055	0.216
3	-48M long (with gables at both ends in 1st story only)	0.0372	(0)	0.090	-0.068	0.216	(0)	0.661	-0.526	-0.010	0.661
4	only 1st story 40M long with temporary gables									0.17 (with top layer on the floor) 0.15(with out top-layer)	
5	48M long upper story tested as a single story building									0.402	

(3) An analysis on the Results of Field Measuring and Testing

The results of field measuring and testing have revealed many interesting phenomena of great importance. Here we will give an analysis on some of the main results.

1) It can be seen from Fig 3 and Fig (4-3) that when a force is applied to the lower storey, its displacement is greater than that of the upper one. This is common for all the buildings we measured.[10] This phenomenon shows that a quite strong reaction is provided by the upper storey.

2) From Tables I and II it can be seen that the magnitude of the secondary factors of space action are of the same order as the main factors. In some cases, the secondary factor is even lager than the main one. It can be seen also that

the values of the combined factors of space action m_1 and m_2 are quite small; sometimes, one of them is negative.

Points 1) and 2) mentioned above reveal that the space action of a multi-story building is quite obvious and the interaction among the storeys is significant, which can not be neglected.

3) Comparing 1 with 2 in Table II, we know that as the length of the building decreases, the the space action increases, while main factors of space action m_{11} and m_{22} as well as the combined factors of space action m_1 and m_2 decrease.

4) From Table I and II it can be seen that m_{21} is quite small and m_{12} is relatively great. For the buildings with the roof of flanged plates or with roof consisting of purlins and flat-tiles, $|m_{12}|$ is larger than m_{11}. For the building with the roof consisting of purlins and flat-tiles, the value of $|m_{12}|$ is greater than that of the building with a roof of flanged plates. This shows that the value $|m_{12}|$ increaces as the rigidity of the roof decreases. Owing to the increase of the value m_{12}, the combined factor of space action m_1 decreases.

5) Comparing 2 and 4 in Table II, it can be seen that the main space action factor m_{11} is smaller than the space action factor of the single storey building. For the building we measured $m_{11}/m=0.145/0.170=0.85$.

6) When designing the experimental building, we take $m_1=0.138$ $m_2=0.55$, both of them are greater than the actual factors of that building, as listed in Table II. Obviously, the design is safe.

In paper [11], we give full details of the anslysing method and of the space action factors of the buildings which has transverse walls in the lower story(s) and the distance between them is quite short, but there are not any transverse walls in the upper storey(s), and also another kind of buildings which has no transvers walls in the the lower story(s) but there are transverse walls in the upper storey(s) and the distance between them is short. Owing to the limited space, we will not discuss this problem here.

4. Conclusion

From the analysis in this article we can conclude that:

(1) There is strong space action in a multistory brick building under wind load. During designing the space action of the building should be taken into account.

(2) According to the analysis method of the multistory building for considering space action given in this paper, the analysis of a building space system can be convertet the analysis of a plane system.

(3) This paper reveals that a multistory brick masonry building can also satisfy the requirement of safety even when the distance between the gables is long (i,e. a rigid-elastic scheme).

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