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INTERACTION AND SEISMIC CAPACITY OF BRICK WALL AND SUPPORTING RC FRAME

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Abstract

Based on pseudo-static test results for 8 specimens of hollow-brick masonry wall supported on RC frame, the interaction and seismic behavior of the brick wall and the supporting RC frame are studied. Under vertical uniform loads, the panel wall and the spandrel RC beam work as a composite deep beam. Under horizontal loads, the composite member works like a shear wall supported by RC Columns, and the ultimate state to determine the shearing capacity of the composite member is the shearing failure of the wall or the damage of the supporting frame caused by plastic hinges. The theoretical analysis based on the finite element method is conducted to study the interaction of the structure. Test and analysis results show that the composite member can serve as the structural member in seismic zone by proper design.

Key Words

Brick wall supported on the RC frame, interaction, seismic capacity, pseudo-static test

Notations

A_{ci} = area of section of structural concrete column
A_{mn} = clear area of the section of brick masonry wall
A_{si} = area of the section of the steel bar
F_y = yielding load when the first plastic hinge is found in the frame
F_u = shearing capacity of the composite structure
F_{u1} = shearing capacity of the masonry wall
f_{cu} = cubic compressive strength of the concrete for frame
f_m = compressive strength of the

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masonry wall

f_t = tensile strength of concrete in structural concrete column

f_V = pure shearing strength of masonry material

f_{VE} = shearing strength of masonry material

f_y = yield strength of steel bar in structural concrete column

φ_i = coefficient, for mid structural concrete column in the wall φ_i=0.5; for side structural concrete column in the wall φ_i =0.25

σ_0 = vertical compressive stress

ξ_n = coefficient considering the influence of vertical compressive stress to shear strength of the masonry material

1 Introduction

Brick/block walls and supporting reinforced concrete frames working together as composite structural members are widely used in multi-story masonry structures when the large space is needed in the first story of the building now in China. The interaction and seismic behavior of the brick/block wall and the supporting RC frame are the key problems in the design of this kind of composite structural member to guarantee the safety of the structure in seismic zone. The interaction between reinforced concrete beam and the adjacent upper brick wall under the vertical load has been proved by tests of 12 specimens in 1952 [Wood 1959]. Then, a lot of papers focused on the study of the interaction of brick wall and continuous wall-beam or RC frame by test or theoretical analysis [Rosenhaupt 1962, Gong and Wu 1995, Gong et al. 2001]. The Design Code for Masonry Structures (GBJ3-88) in China includes some regulations for one-span frame under this condition. But in seismic regions, whether the interaction exists in or after earthquake and how to design this kind of structure still need to be studied. So the seismic behavior of the brick wall and the supporting RC frame is the key problem to guarantee the safety of the structure.

In this paper, pseudo-static tests for 8 specimens of hollow-brick masonry wall supported on the RC frame and the theoretical analysis based on the finite element method are conducted. The damage mechanism and the seismic bearing capacity of the composite structural member are studied based on the test and theoretical results.

2 Test study

2.1 Specimen details

Eight half-scale specimens were constructed. The dimensions of the specimen are showing in Table 1 and Figure 1. In these specimens, FWB1-1~3 are masonry walls supported by one-span RC frames, FWB2-1~3 are supported by two-span RC frames and FWB3-1~2 are supported by two-span RC shear wall-frame composite structures.

2.2 Mechanical properties of materials

Table 1 presents the main mechanical properties of the materials for specimens. The cubic compressive strength of the concrete for frame is between 26.1~31.1MPa. The average cubic compressive strength of the concrete for structural concrete columns and the top beam in the wall is between 22.3~24.1MPa. The average compressive

strength of the masonry wall is between 3.31~4.07MPa. The average shear strength of the masonry wall is between 0.29~0.47MPa. The yield strength of the steel bar is between 288~385MPa, the tensile ultimate strength of the shear bar is between 411~586MPa.

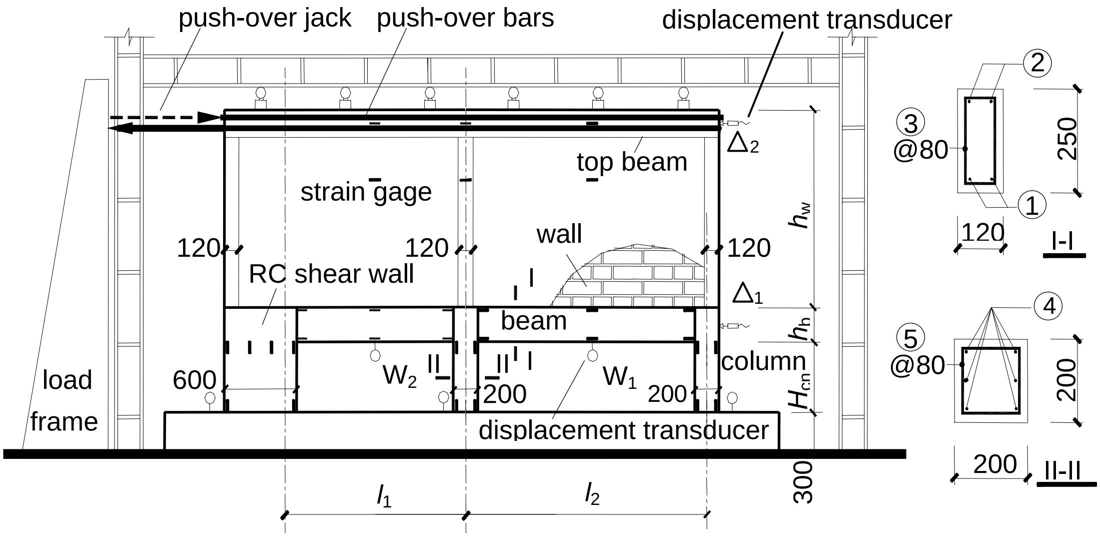

Figure 1 Test setup

2.3 Test set-up

The pseudo-static test set-up is shown in Figure 1. Five or six jacks were used to apply a uniform compressive stress on the top of the wall in the test to simulate the action of the vertical load. The specimen was subjected to a cyclic loading at the concrete top beam. Data from load cells, displacement transducers, and strain gauges were acquired using a computer controlled data acquisition system.

First, the vertical load from 180 to 450 kN was applied on the top beam. The average stress σ_o in the masonry wall is between 0.64 and 0.91MPa to simulate 6~7 stories vertical characteristic load in a real structure.

Second, the horizontal cyclic load was applied step by step using force-controlled method till the wall was cracked. The lateral displacement Δ_1 on the top of the frame and Δ_2 on the top of the wall corresponding to every cyclic step were recorded. After cracking, displacement-controlled loading method was employed to make the test continued until the specimen lost its ability to resist the horizontal load.

Last, except FWB 2-2 which was broken near the top beam under horizontal cyclic loading, the vertical load from 300 kN to 1020 kN was applied on the top beam. The average stress σ_l in the masonry wall is between 1.14~2.02 MPa .

3 Analysis of test results

3.1 Interaction of masonry wall and supporting frame under vertical load

Under vertical load applied on the specimens, no cracks were found on the surface of the specimens. Comparing the first deflection w_{1o} and w_{1o}/l_1 in Table 2 with a common

RC beam under same vertical load, the interaction between reinforced concrete frame and the upper brick wall can be obviously observed.

Table 1 Details of specimens

Specimens	FWB1-1	FWB1-2	FWB1-3	FWB2-1	FWB2-2	FWB2-3	FWB3-1	FWB3-2
l_1	2000	2000	2000	2000	2500	2500	2000	2000
l_2	—	—	—	2000	1500	1500	1500	1500
h_w	1360	1280	1360	1325	1260	1325	1260	1430
H_{cn} (H_{wn})	590	670	590	625	690	625	690	520
h_b/l_1	1/8	1/8	1/8	1/8	1/10	1/10	1/8	1/8
h_w/l_1	0.680	0.640	0.680	0.663	0.504	0.530	0.630	0.715
σ_o (MPa)	0.682	0.909	0.909	0.893	0.893	0.643	0.659	0.878
Bars ①	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12
Bars ②	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12	2$\underline{\phi}$12
Bars ③	ϕ6	ϕ6	ϕ6	ϕ8	ϕ8	ϕ8	ϕ8	ϕ8
Bars ④	6$\underline{\phi}$20	6$\underline{\phi}$18	6$\underline{\phi}$20	6$\underline{\phi}$22	6$\underline{\phi}$20	6$\underline{\phi}$20	6$\underline{\phi}$18	6$\underline{\phi}$18
Bars ⑤	ϕ8	ϕ8	ϕ8	ϕ8	ϕ8	ϕ8	ϕ6	ϕ6
f_{cu} * (MPa)	28.0	27.3	29.3	29.3	26.1	26.1	29.5	31.1
f_{cu} ** (MPa)		22.3			28.2		24.1	
f_m *** (MPa)		3.31			3.47		4.07	
f_v **** (MPa)		0.37			0.29		0.47	

All of specimens:

- Wall: h = 115mm
- Beam: $b_b \times h_b$ = 120×250mm
- Column: $b_c \times h_c$ = 200×200mm
- Top Beam: $b_t \times h_b$ = 120×200mm, 4ϕ8, ϕ6@200
- Structural Concrete Column : $b_s \times h_s$ = 120×120mm, 4ϕ6, ϕ6@200
- Reinforced Concrete Shear Wall (if there is)
  $b_w \times h_w$ = 150×600mm,4$\underline{\phi}$10 + 4$\underline{\phi}$14, ϕ6@150

* the cubic compressive strength of the concrete for the frame. ** the cubic compressive strength of the concrete for structural concrete columns and top beams. *** the compressive strength of masonry walls. **** the pure shearing strength of masonry walls

3.2 Horizontal shearing capacity and deforming ability

Values of the shearing capacity and the displacement of specimens in tests are summarized in Table 2 and Figure 2. In Table 2 , σ_o is the uniform compressive stress applied on the top beam during horizontal loading applied on the top of the specimen, cracking load is the horizontal applied force when cracks were found on the RC beam or RC column or masonry wall or RC shear wall, Δ_{2u} is the ultimate lateral displacement on the top of the specimen, Δ_{1u} is the max displacement on the top of the frame, Δ_{1y} and Δ_{2y} are the displacements corresponding to the horizontal load when the first plastic hinge is found in the frame. According to the seismic defensive criterion of China, in the zone whose seismic defensive intensity is 7, these specimens would not crack under frequent earthquake action comparing the minimum cracking load with the vertical load. Comparing the horizontal ultimate load with the vertical load, it can be seen that these specimens could averagely bear simulated 1.38 times of very rear earthquake action proposed by Chinese code.

3.3 Typical failure modes under horizontal load

Figure 3 shows the failure modes for some of testing specimens. It can be seen that

after the first plastic hinge appeared near the support of the RC frame beam the ultimate state to determine the shearing capacity of the composite member is the shearing failure of the wall. A lot of horizontal cracks would appear on the surface of the masonry wall, some cracks would get through into the structural concrete columns.

Table 2 Testing and calculation results

Specimens		FWB1-1	FWB1-2	FWB1-3	FWB2-1	FWB2-2	FWB2-3	FWB3-1	FWB3-2
Crack-ing Load (kN)	Beam	Push 30	Push 40	Pull 60	Pull 30	Pull 40	Pull 120	Pull 150	Push 105
	Wall	Pull 45	Push 40	Push 45	Pull 30	Push 40	Pull 80	Push 150	Push 160
	Column	Push 96	Push 150	Pull 100	Push 270	Pull 200	Pull 160	Pull 270	Push 300
	Rc Wall	—	—	—	—	—	—	Pull 270	Push 260
Yield-ing Load *	F_y^E (kN)	96	90	108	Pull 240	Push205	Push200	Pull250	Push295
	F_y (kN)	104	89	91	Pull 234	Push199	Push200	Pull226	Push290
	F_y^E / F_y	0.923	1.011	1.187	1.026	1.030	1.000	1.106	1.017
Break-ing Load **	F_u^E (kN)	Push124 Pull 107	Push150 Pull 148	Push162 Pull 166	Pull 300 Push203	Push226 Pull 231	Push255 Pull 230	Pull 295 Push310	Push350 Pull 348
	F_{u1} (kN)	129	141	141	247	247	222	263	286
	F_u^E / F_{u1}	0.959 0.827	1.062 1.048	1.146 1.174	1.213 0.821	0.915 0.936	1.151 1.038	1.121 1.178	1.223 1.126
	F_u' (kN)	111	119	119	205	205	189	241	256
	F_u^E / F_u'	1.118 0.965	1.265 1.248	1.365 1.398	1.465 0.991	1.105 1.130	1.351 1.218	1.222 1.284	1.369 1.361
F_u (kN)		104	89	91	Pull 234	Push199	Push200	Pull226	286
Later-al Dis.	$\triangle_{2u}$ (mm)	13.4	16.7	24.3	14.9	12.0	16.2	22.4	22.6
	$\triangle_{2y}$ (mm)	4.6	2.6	3.9	5.4	4.9	3.7	4.7	3.5
	$\triangle_{1u}$ (mm)	7.1	6.5	10.5	7.1	8.4	9.0	7.0	11.7
	$\triangle_{1y}$ (mm)	2.9	2.1	2.1	3.1	4.1	2.9	2.2	2.7
	$\triangle_{2u} / \triangle_{2y}$	2.91	6.42	6.23	2.76	2.45	4.37	4.77	6.45
	$\triangle_{1u} / \triangle_{1y}$	2.45	3.10	5.00	2.29	2.05	3.10	3.18	4.33
First vertical Load P_o (kN)		180	240	240	450	450	324	324	432
σ_o (MPa)		0.682	0.909	0.909	0.893	0.893	0.643	0.659	0.878
First Deflection w_{1o} (mm)		0.29	0.48	0.40	0.41	0.74	0.42	0.36	0.29
w_{1o} / l_1		1/6993	1/4167	1/5000	1/4878	1/3397	1/5952	1/5556	1/6897
Last vertical Load P_l (kN)		300	480	390	1020	—	648	600	600
σ_l (MPa)		1.137	1.818	1.477	2.024	—	1.286	1.220	1.220
Last Deflection w_{1l} (mm)		1.17	3.21	2.05	2.93	—	4.06	0.72	1.58
w_{1l} / l_1		1/1709	1/623	1/976	1/683	—	1/615	1/2083	1/949
P_l / P_o		1.667	2.000	1.625	2.267	—	2.00	1.852	1.389

* yielding load is the horizontal load when the first plastic hinge is found in the frame

** breaking load is the horizontal load when shearing failure occurs in the wall

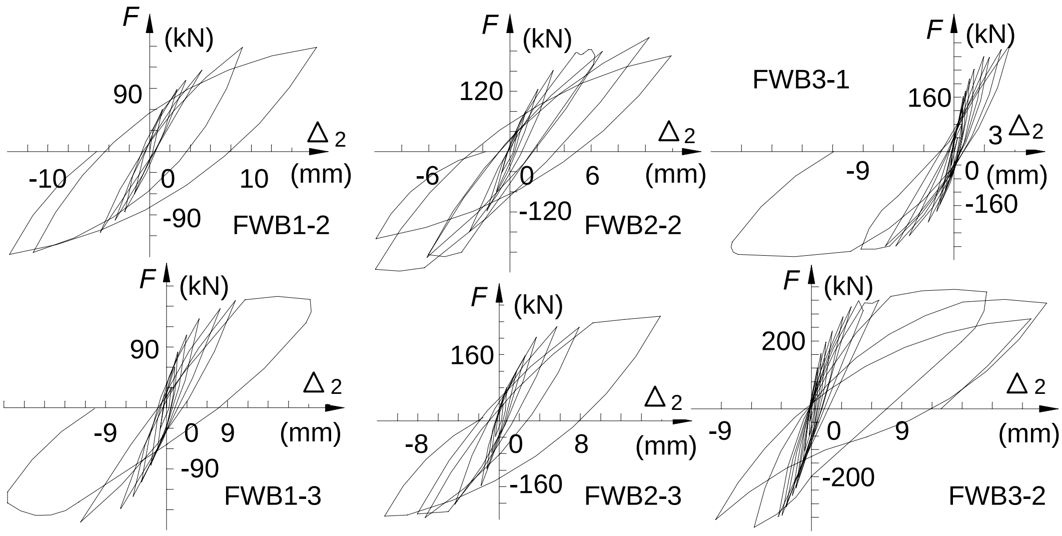

Figure 2 Load-displacement relationship curves for some of specimens

3.4 Residual vertical bearing capacity of the specimen after horizontal loading

In order to study the behavior of the damaged specimen after earthquake, vertical load was applied on the top beam step by step. Even though there are lots of cracks, each composite member, except FWB2-2, can still work well till average compressive stress σ_l reaches to 1.14~2.20MPa. Because some hollow-bricks drop from the top corner of the masonry wall, FWB2-2 could not bear vertical load anymore. Table 2 shows that the ratio of the deflection to the span under last vertical load is between 1/615 and 1/2083, and the composite member could bear about 1.4 times of characteristic uniform load at least. It can be concluded even though the specimen damaged by the earthquake (horizontal action), if the masonry wall did not collapse, the interaction between RC frame and adjacent wall still exists.

4 Calculation of horizontal bearing capacity

4.1 Calculation method

Because the ultimate state to determine the horizontal bearing capacity of the composite member is the shearing failure of the wall or the damage of the supporting RC frame caused by enough plastic hinges, the smaller value calculated from these two kind of ultimate states is the horizontal bearing capacity of the composite structural member of brick wall and supporting RC frame. Because of the difficulty to estimate all of plastic hinges in RC frame using elastic analysis method, it is assumed in the design that the ultimate state for supporting RC frame is the state when the first plastic hinge appears in the frame.

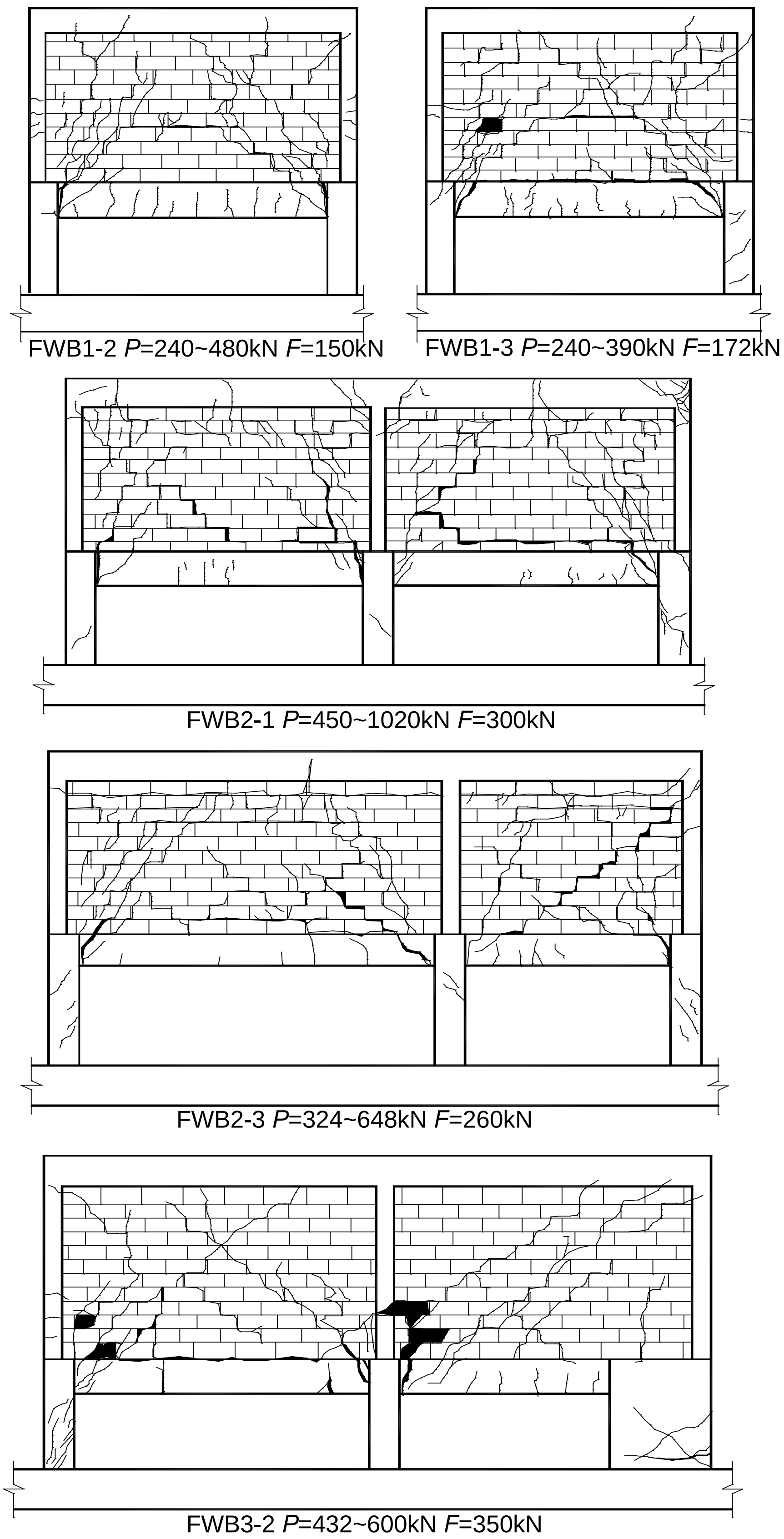

Figure 3 Failure modes for some of specimens

According to the behavior of the specimens observed in the pseudo-static test, the shearing capacity of the masonry wall governs the specimen bearing capacity of the composite structural member and it can be estimated by taking into account the coupling action of the hollow-brick wall, structural concrete columns and steel bars. Based on the test results, the calculating formula is recommended as follows:

$$F_{u1} = f_{vE} A_{mn} + \sum_{i=1}^{n} \varphi_i f_t A_{ci} + 0.08 \sum_{i=1}^{n} f_i A_{si} \tag{1}$$

in which, $f_{vE} = \xi_N f_v$, $\xi_N = \frac{1}{1.2}\sqrt{1+\frac{\sigma_0}{f_v}}$.

To calculate the horizontal bearing capacity F_y when the first plastic hinge appears in the frame, a finite element analysis method is employed. The details of method will be published in another paper. But the finite element model for the composite structure of brick wall and supporting RC frame is shown in Figure 4. Using the model shown in Figure 4, inner forces for the critical sections of frame beams and columns, under vertical load P_o and horizontal load F can be calculated. When the inner forces in one of the critical sections reach the bearing capacity of the section in RC frame, which can be deduced according to the code for Design of Concrete Structures (GB50010-2002) in China, the corresponding horizontal force can be taken as the shearing capacity F_y of the composite structure governed by the supporting RC frame. The results for the test specimens show that the first plastic hinge appears in the beam near its support.
Knowing the shearing capacity of the masonry wall F_{u1} and the yielding force of F_y, the shearing capacity for the composite structure of masonry wall and supporting RC frame can be calculated using Equ. (2).

$$F_u = \min(F_{u1}, F_y) \tag{2}$$

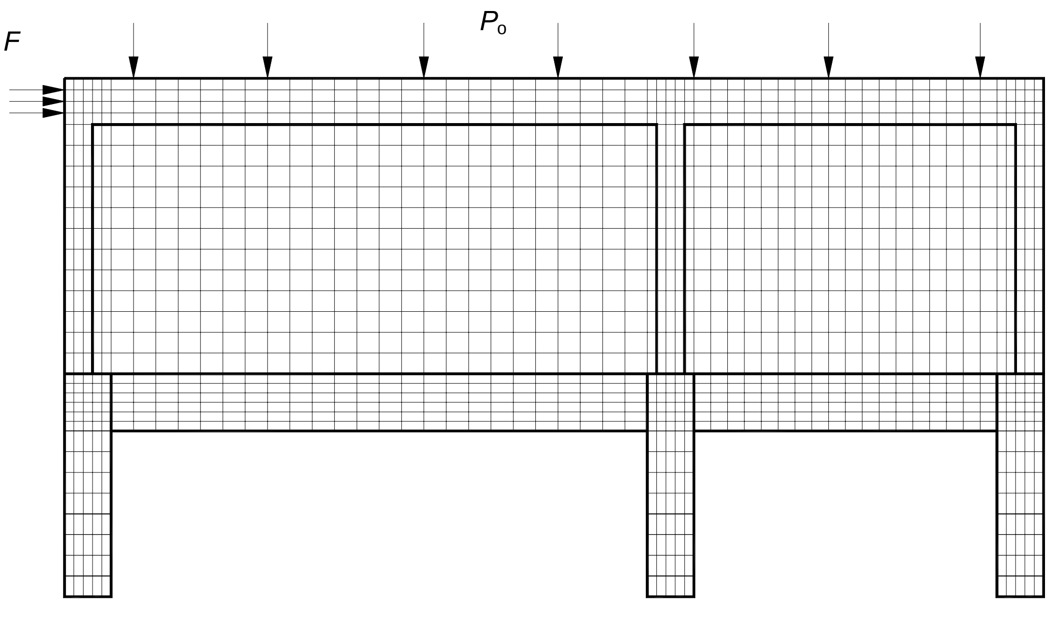

Figure 4 Finite element analysis model

4.2 Comparison of testing and calculation results

Table 2 gives calculating and testing results of the yielding load (F_y and F_y^E), the shearing capacity of the masonry wall (F_{u1}), and the shearing capacity of the composite structure (F_u and F_u^E) for all of the specimens. And also the calculation results of the shearing capacity of the composite structure (F_u') using the method proposed by the Code for Design of Masonry Structures (GB50003-2001) in China are listed in the table. Comparing the results shown in Table 2, it can be concluded that the proposed method in this paper is accurate enough to estimate the shearing capacity of these testing specimens under earthquake action. For the purpose of the application, the method needs to be verified with more other experiments.

5 Conclusions

Based on pseudo-static tests for 8 specimens of hollow-brick masonry wall supported on the RC frame, the interaction between masonry wall and supporting RC frame under vertical and horizontal loads are proved, the ultimate state to determine the shearing capacity of the composite member is the shearing failure of the wall or the yielding of the supporting frame. Test and theoretic analysis results show that the supporting RC frame and the adjacent masonry wall can work together well and the composite member can serve as the structural member in seismic zone by proper design. If the masonry wall had not collapsed in the earthquake, the interaction would exist. The calculation equation for the shearing capacity of the masonry wall and supporting RC frame has good accuracy. More experiments and elasto-plastic analysis for different kinds of composite structural members of brick wall and supporting reinforcement concrete frame are going to be done in the future.

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