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Structural Identification on Masonry Infilled Reinforced Concrete Frames on Soil Foundation

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ABSTRACT

Static and dynamic tests were conducted on a 4-layer frame reinforced concrete model with plate type independent footings on soil foundation in 3 different cases. The purpose was to study how the dynamic behavior of reinforced concrete (RC) frame would be affected by masonry infill walls. Three different cases were designed to figure out the interaction mechanism between the frame and the infill walls. The 1st case was a bare frame. The 2nd case was an unattached-filling frame with masonry bricks settled on three transverse beams. The 3rd case was the general filling frame. The 2nd case was to investigate the influence of mass increment on the 2nd story to the dynamic behavior of frame structure, while the 3rd case is to address the influence of both mass and stiffness increment on the dynamic behavior of the structure. Multiple reference impact tests (MRIT) were conducted on the structure to obtain the modal characteristics. Static experiments were also conducted to obtain the lateral deflection and the corresponding strain distribution on the column. All cases were simulated in the finite element (FE) software, and the centerline FE model was firstly drawn in AutoCAD and imported into the model in SAP2000 in the 1st case. The shell element model and diagonal strut model were utilized to modify the masonry infilled wall and the rationality of the model was proved by comparing the calculated results with the experiment results. In addition, the modal information in MRIT was utilized to calculate modal flexibility, which was in further used to calculate the possible displacement, and it was compared with the static experiment results and calculated values of FE models.

Keywords: Structural identification; Masonry infilled wall; FE model calibration; Static test; Multiple reference impact test (MRIT)

INTRODUCTION

A lot of buildings are constructed with unreinforced masonry infill walls for architectural reasons or aesthetic needs, however, infilled frames are complex structures which exhibit a highly nonlinear inelastic behavior resulting from the interaction of the infill wall and the surrounding frame[1]. And the structural engineers always ignored the influence of infill wall when designing the configuration of structure, which may lead to predict the lateral stiffness, strength, and ductility of the structure

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inaccurately. Therefore, the analytical modelling of the infilled frames represents an important issue for researchers and engineers.

In 1960, Polyakov [2] raised that the diagonal strut was utilized to represent the infill wall. In 1961, Holmes [3] came up with a pin-jointed diagonal strut of the same material and the same thickness as the infill wall. In 1969, Smith et al. [4] proposed the evaluation of equivalent width, λ, as a function of panel-to-frame-stiffness ratio. In 1985, Thiruvengadam [5] pointed out that a multiple-strut model to simulate the effect of infill wall, and it was a moment-resisting frame with a large number of pin-jointed diagonal and vertical struts. In 1991, Chrysostomou [6] put forth six compression-only inclined struts in order to obtain the response of infilled frames during earthquake by taking both stiffness and strength degradation of infill wall into consideration. In 1992, Paulay et al. [7] showed that a high value of width of diagonal strut will cause a stiffer structure and potentially higher seismic response. In 1997, Crisafulli [1] investigated the influence of different multiple-strut models on the structural response of RC infilled frames, focusing on the structure stiffness and the actions induced into the surrounding frame. In 2007, Crisafulli et al. [8] proposed a macro-model to inspect the effect of infill walls in a reasonable and simple way, and the model is simplified as a four-node panel element with the beam-column joints as the nodes.

Despite this 60-year-long effort, the widely accepted macro-model was the diagonal-strut model, and there are basically two kinds of diagonal-strut models: single-strut model and multiple-strut model. On one hand, the single-strut model, very simple to apply in general-purpose FE software, but it cannot describe the local effects occurring in the surrounding frame. On the other hand, the multiple-strut models, are more capable of both describing the infill and capturing its interaction in the surrounding frame, cannot be used in FE software of general purpose because of complexity of modelling. It can be inferred that the issue of modelling infill walls in frame structure is still an unsolved problem.

This paper presents a reasonable infilled frame model to be implemented in FE analysis software, which is based on experimental data from a series of dynamic and static tests using RC infilled frame in laboratory. The model ensured that the space geometry relationship of infilled frame model was consistent with the original structure. The shell element and diagonal strut were utilized to simulate the infilled wall and the calculated values were compared with experimental data to verify the rationality of the FE models.

RC FRAME STRUCTURE EXPERIMENT

The experiment was conducted in the Structural Laboratory of Hunan University. The experiment object is a four-story RC structure model which has independent footings on soil foundation. The bottom floor has height of 1.333 meters, and the height of the 2nd to 4th layer is 1 meter. The reinforcing steel bars in beams, panels and columns are all HPB235. The grade of the strength of concrete is C25 and the floor thickness is 30mm. The detailed structural information can be found in Xie [9]. The experimental modal test and static test were conducted on this frame.

Modal Test

MRIT was conducted to research the influence of infilled wall to the dynamic properties of the frame structure. Three different cases were designed as shown in Fig.1(a)-(c): (a) the bare frame, (b) the unattached-filling frame, and (c) the infilled frame. The difference of case 2 and case 3 was designed to differentiate the influence of the mass and stiffness contribution to the dynamic characteristic of the frame separately. So the clay brick was only piled up on the position of desired infilled walls in the 2nd floor without contacting with the surrounding beams and columns.

MRIT was conducted on the frame to capture the modal information of the frame structure. The layout of acceleration sensors for the structure was as shown in Fig.1(d): No.1~10 were installed along X horizontal direction, while No.15~29 instrumented in Y horizontal direction. No.11~14 and No.33~35 were put on the surface of the foundation slab in vertical direction for measurement of the foundation vibration. DP730 dynamic data acquisition was used for collecting the dynamic impulse force and response signals in time domain, and the sampling frequency was set as 256Hz. Autopower spectral density and crosspower spectral density were obtained to the modal test results were as shown in Table 1. The results showed that, compared with the bare frame, the modal frequencies of unattached-filling frame decreased significantly with the increasing of the damping ratio. And the first X translational frequency decreased up to 5.92%. According to the data of infilled frame, the stiffness increment has a huge influence on the Y translational frequencies and torsional modal frequencies of the structure. The experimental results showed that the 1st X translational frequency rates increased to 2.74%, while the 1st Y translational frequency and the 3rd torsional frequency is increased by 26.16% and 22.48% , respectively. Furthermore, the 4th Y translational and torsional modes are disappeared. The changment of modal frequency were obvious relied on the position and infilled status of the infill wall, there were 3 infill walls arranged along the span, so the Y plane stiffness of frame increased significantly and the changement of X plane stiffness was not obvious.

Static Test

The main purpose of the static test is to measure the lateral deformation and the stress in the bare frame and the infilled frame under the external lateral loads within the range of elasticity. The load was acted at the beam-column joints in Y plane on the 4th story. The loading in static test is from the mechanical jack controlled by pressure sensors and the counterforce of jack is effect on transverse wall in adjacent building. As shown in Fig. 1, 5 displacement gages were instrumented to measure the displacement at each story as well as the column base, and 18 strain gauges were installed to measure the concrete strain at the upper and lower surface of the floor as well as the independent foundation. TDS-530 strain test system was used for collecting the data from the pressure sensors, strain gauges and displacement gages.

a) Case 1 b) Case 2 c) Case 3 d) Layout of sensors

Fig. 1. Three cases of modal test and the layout of sensors

Table 1. The frequencies and damping ratios of three cases

Modal para.	Case 1		Case 2			Case 3		
	Freq.	Damp.	Freq.	Diff.	Damp.	Freq.	Diff.	Damp.

		(Hz)	(%)	(Hz)	(%)	(%)	(Hz)	(%)	(%)
1st	X dir.	7.43	2.33	6.99	-5.92	9.93	7.19	-3.18	2.17
	Y dir.	7.41	2.70	7.07	-4.61	8.21	9.01	21.55	2.62
	Torsional dir.	10.00	1.94	9.72	-2.79	6.73	11.97	19.69	1.96
2nd	X dir.	24.98	1.77	23.71	-5.08	4.34	21.86	-12.46	1.50
	Y dir.	24.62	2.40	24.09	-2.14	7.87	22.70	-7.92	1.74
	Torsional dir.	32.24	2.12	30.63	-4.98	4.91	29.76	-0.77	1.39
3rd	X dir.	47.67	1.18	45.53	-4.48	3.64	47.58	-0.17	0.99
	Y dir.	47.64	1.56	45.98	-3.49	2.75	58.71	23.2	0.96
	Torsional dir.	60.52	1.15	59.99	-0.87	1.89	74.55	23.2	2.18
4th	X dir.	72.25	1.04	70.28	-2.72	1.71	70.92	-1.85	0.98
	Y dir.	71.06	1.17	69.29	-2.49	4.39	/	/	/
	Torsional dir.	92.09	1.08	89.93	-2.35	1.96	/	/	/

FE MODELING

Case I FE Model Analysis

The centerline FE model was firstly drawn in AutoCAD and imported into the model in SAP2000. The space geometry relationship of different components interact in different 3D planes, thus the link element was utilized for connecting the gaps between the beams and columns of the model. The detailed beam-column joint was as shown in Fig.2 (b)-(c), and the comparison of model and actual structure can be found in Table 2. The results showed that the first X translational frequency is is quite close to the measured value, and the relative error rate is only 0.37%. Furthermore, the relative errors of all X and Y translational frequencies are less than 5%, and the maximum relative error of torsional modal frequency is only 7.92%. It has to be emphasized that the model didn't take the foundation stiffness into consideration because of the calculation is lower than measured values. Above all, it can meet the requirements of engineering precision and the calculated results match well with the measured values.

a) The bare FE model b) The beam-column joint picture (c) The beam-column joint in FE model

Fig. 2. FE modeling of Case 1 frame

Table 2. Comparison of calculated results and measured values of bare frame

Modal para.	X dir. Cal. results(Hz)	X dir. Rel. error(%)	Y dir. Cal. results(Hz)	Y dir. Rel. error(%)	Torsional dir. Cal. results(Hz)	Torsional dir. Rel. error(%)
1st	7.39	0.37	7.54	-1.71	9.44	5.65
2nd	24.12	3.20	24.51	0.42	30.37	5.71
3rd	45.77	4.06	46.36	2.69	56.46	7.92
4th	70.49	2.72	70.82	2.25	86.05	6.67

Case II FE Model Analysis—Unattached-Filling Frame Model

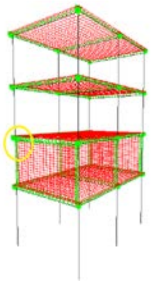
In case II, the bricks were piled up on the surface of the transversal beams and the line loads of the clay brick is 1.65kN/m. In the SAP2000 FE modeling, the load of clay brick was set as the mass on the 1st layer transvers beam elements and as part of the mass matrix. The comparison of calculated results and measured values was as shown in the Table 3, and the results showed that the minimum of relative errors is -3.31% and all X and Y translational frequencies are less than 11%, but the maximum relative error is 27.60%.

Table 3. Comparison of calculated results and measured values of unattached-filling frame

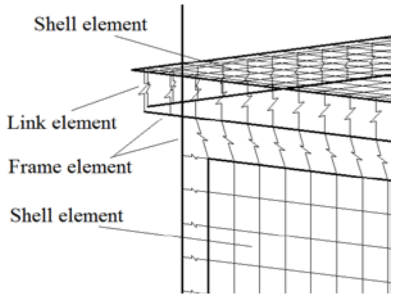
Modal para.	X dir. Cal. results(Hz)	X dir. Rel. error(%)	Y dir. Cal. results(Hz)	Y dir. Rel. error(%)	Torsional dir. Cal. results(Hz)	Torsional dir. Rel. error(%)
1st	7.22	-3.31	7.36	-4.09	9.20	5.04
2nd	21.13	10.87	21.44	10.99	26.36	13.82
3rd	40.75	10.50	41.64	9.44	50.53	27.60
4th	67.86	5.85	68.41	3.81	82.93	7.67

Case III FE Model Analysis--Infilled Frame Model 1

The shell element model was utilized to simulate the infilled wall. To ensure the model was consistent with the structure, the size and the thickness of the shell element were chosen the same as the original masonry structure. Based on the Code for Design of Masonry Structures (GB50003-2011), the Poisson's ratio of the shell element is set as 0.15. The infilled wall stiffness will be changed with the changment of the elastic modulus of the shell elements and the figures of the model and the beam-column joint are shown as follows. The results of modal frequencies and mode shapes were obtained by analytical modal analysis when the elastic modulus of the shell elements is 1800MPa and the data was as shown in the Table 4. The results revealed that the minimum relative error is 0.04% from the 1st torsional frequency and the maximum relative error is the 3rd X translational frequency, which is 12.95%, and most of the relative errors of modal frequencies are less than 10%. It is concluded that the calculated results matched well with measured values and the model on the whole is consistent with the original structure.



a) Infilled frame model 1



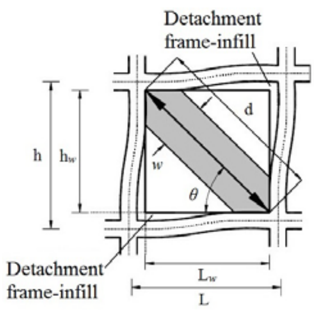
b) The detailed beam-column joint

Fig. 3. The infilled frame model 1 and beam-column joint

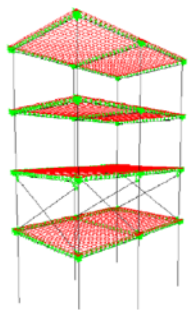
Case III FE Model Analysis--Infilled Frame Model 2

In the early 1960s, Polyakov [1] suggested the possibility of considering the effect of the infilling in each panel as equivalent to diagonal bracing. And Holmes [2] proposed the “one-third” rule that the width of equivalent diagonal strut is one-third of the diagonal length of the masonry panel, which is the first function to describe the relation between the infilled wall and the frame. The diagonal-strut model which is the most common is to simulate the infilled wall, so the infilled frame model is named as infilled frame model 2. The actual masonry infilled wall is the brick masonry structure and the material are MU10 sintered ordinary bricks and M2.5 mortar. According to the Code for Design of Masonry Structures(GB50003-2011), the compressive strength design value of masonry should be 1.30MPa, and the elastic modulus and Poisson's ratio should be 1807MPa and 0.15 separately.

Based on experimental data from a series of tests using masonry-infilled frames, Li [10] raised that the equivalent width of diagonal-strut should be 3/5 of the length of diagonal side when the infilled wall is rigidly fixed at both ends, so this paper refer to his results and set the width of diagonal struts as 1118mm, and the diagonal struts are rigidly fixed with the frame elements. The figure of the infilled frame model and the table of comparison of calculation results and measured values are shown as follows. The data indicated that the maximum relative error is 14.23% from the 3rd X translational frequency, while the 2st Y translational frequency is only -0.57%, and the relative error of torsional frequencies are less than 10%. In conclusion, the model calculation value is close to the measured data and the infilled frame model is reasonable.



a) Equivalent diagonal strut [11]



b) Infilled frame model 2

Fig. 4. The diagonal strut and infilled frame model 2

Table 4. Comparison of calculated results and measured values of infilled frame model

Modal para.	Infilled frame model 1		Infilled frame model 2	
	Cal. results(Hz)	Rel. error(%)	Cal. results(Hz)	Rel. error(%)

1	X dir.	7.39	-2.78	7.25	-0.83
	Y dir.	9.94	-10.32	10.08	-11.88
	Torsional dir.	11.99	0.04	12.00	-0.08
2	X dir.	20.75	5.08	20.66	5.49
	Y dir.	22.54	0.70	22.83	-0.57
	Torsional dir.	27.54	7.68	27.63	7.38
3	X dir.	41.42	12.95	40.81	14.23
	Y dir.	57.04	2.84	57.70	1.72
	Torsional dir.	67.66	9.24	67.90	8.92
4	X dir.	69.73	1.68	68.88	2.88
	Y dir.	/	/	/	/
	Torsional dir.	/	/	/	/

DEFLECTION ANALYSIS BY MODAL FLEXIBILITY

Zhou [12] proposed two modal flexibility estimation methods can directly extract modal parameters from input and output dynamic signals to calculate the modal flexibility information: the computing method based on the mass-normalized mode shapes and the method of extracting modal flexibility when *w* is equal to zero in frequency response function.

In order to verify the rationality of the infilled frame model, the displacements of the floors were obtained by loading 5kN on the forth layer of the infilled frame model 1and 2, and the comparison of the calculation results and measured values are as shown in Table 4. The results showed that the minimum relative error of the displacement of model 1 is -2.61% ,which is from the 4th layer, while the maximum of relative error is 1st layer, which is 23.64%, and the displacement of the 4th layer of model 2 is the nearest to the measured value, the relative error is only -0.25%, but the relative error of the 1st layer is 25.37%. The dynamic test is under the condition of micro-amplitude vibration, while the great displacement of floors and strain amplitude take place in the static load test, so the foundation stiffness have a large impact on the structure. Therefore, the relative errors of the 3rd and 4th stories are less than the 1st story.

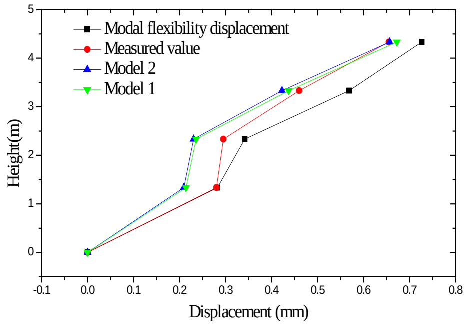


Fig. 5. Comparison of calculated results and measured values of infilled frame model 1 and 2

Table 4. Comparison of calculated values and measured values of infilled frame model 1 and 2

Modal flexibility	Mea. values(mm)	Infilled frame model 1		Infilled frame model 2	
		Cal. results(Hz)	Rel. error(%)	Cal. results(Hz)	Rel. error(%)
1st	0.66	0.67	-2.61	0.66	-0.25

2nd	0.46	0.44	5.02	0.42	8.16
3rd	0.30	0.24	20.14	0.23	21.97
4th	0.28	0.21	23.64	0.21	25.37

CONCLUSIONS

A macro-model for frame structure and two kinds of models for masonry infill walls were built in this paper. The comparisons between experimental data and analytical results indicated that the infilled frame can be properly represented by the reasonable model and the infill walls can be simulated by the shell element or diagonal-strut model in FE software. It's evident that the accuracy of model can be improved by modified the space geometry relationship of different components of structure. Although the diagonal-strut is widely accepted as a model to present the infill walls, the shell element model can be used as a simple and rational way to simulate the masonry infill walls.

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