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INFLUENCE OF IN-PLANE AND OUT-OF-PLANE INTERACTION OF INFILL WALLS ON GLOBAL COLLAPSE RESISTANCE CAPACITY OF INFILLED RC FRAME

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Keywords: In-Plane and Out-of-Plane Interaction, Infill Walls, Infilled RC Frame, Incremental Dynamic Analysis, Global Collapse Resistance capacity.

Abstract. *Firstly, the model using beam-column elements with fiber discretization to consider in-plane and out-of-plane interaction of infill walls was elaborated. Then, in order to validate the proposed model, a shaking table test model of a 4-storey infilled RC frame was modeled and analyzed via the finite element software, OpenSees. Comparison with the experimental and simulated results indicates that the numerical model considering in-plane and out-of-plane interaction of unreinforced masonry infill walls is valid for modeling the infilled RC frame structure. Then, based on the calibrated numerical model, a three-dimensional model of an infilled RC frame teaching building was established via OpenSees. And static pushover analysis and incremental dynamic analysis under 24 suites of ground motion records were carried out on the model with and without considering in-plane and out-of-plane interaction of unreinforced masonry infill walls. Furthermore, incremental dynamic analysis results were used to evaluate the global collapse resistance capacity of the structure with 50% collapse probability. Analytical results show in-plane and out-of-plane interaction of infill walls has a significant influence on the seismic behavior of the structure. The model without considering in-plane and out-of-plane interaction of infill walls shows obvious degradation. Without accounting for in-plane and out-of-plane interaction of infill walls, the global collapse resistance capacity of the structure will be underestimated obviously.*

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1 INTRODUCTION

The Great Wenchuan Earthquake in 2008 in China and the Haiti earthquake in 2010 caused serious casualties and property losses due to the collapse of structures [1, 2]. Therefore, how to evaluate the collapse resistance capacity of the structure subjected to strong or catastrophic earthquakes has become an important issue in the earthquake engineering [3]. Nowadays, the researches on global collapse resistance capacity evaluation mainly focused on the bare frame of the building. And the influence of some nonstructural components such as infill walls was not well included. For analyzing and designing the infilled RC frame structure, only the influence of infill walls to lateral stiffness of structures was considered. The interaction between infill walls and the main structure was neglected.

The mechanism of the interaction between the main structure and infill walls is complicated and it is also influenced by many factors, so there is still no consensus on how to deal with this issue rationally [4-6]. Based on the Strut and Tie model, Hashemi proposed an approach to model both the in-plane (IP) and out-of-plane (OOP) response of the infill, as well as the interaction between IP and OOP capacities. But this model is only appropriate for an analysis based on small displacement, and it is not appropriate when the model is subjected to large in-plane load and out-of-plane displacement. Based on these concerns, infill model using beam-column elements with fiber discretization is proposed by Kadysiewski, which can obtain relatively stable numerical simulation results [7].

In this paper, the model using beam-column elements with fiber discretization to consider the IP and OOP interaction of infill walls was elaborated firstly. Then, in order to validate the proposed model, a shaking table test model of a 4-storey infilled RC frame was modeled and analyzed via the finite element software, OpenSees. Based on the calibrated numerical model, a three-dimensional model of an infilled RC frame teaching building was established. And static pushover analysis and incremental dynamic analysis under 24 suites of ground motion records were carried out on the model with and without considering the IP and OOP interaction of unreinforced masonry infill walls. Furthermore, incremental dynamic analysis results were used to evaluate the global collapse resistance capacity of the structure with 50% collapse probability.

2 THE INFILL WALL MODEL ACCOUNTING FOR IP AND OOP INTERACTION

An infill model using beam-column elements with fiber discretization is shown in Figure 1 [7]. For each infill panel, representing a single bay in a single story, the model consists of one diagonal member. That member is composed of two beam-column elements, jointed at the midpoint node. This node is given a lumped mass along the OOP direction.

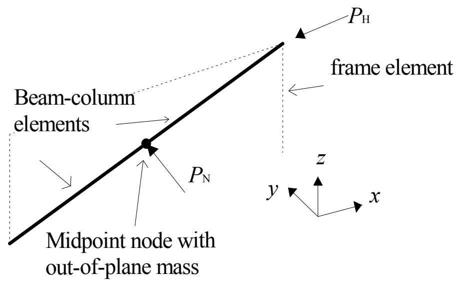


Figure 1: The infill model using beam-column elements with fiber discretization.

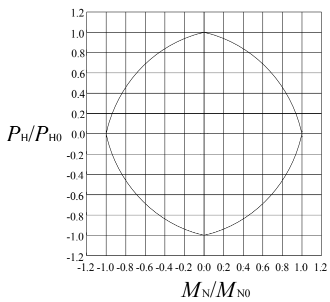


Figure 2: *P-M* interaction curve of typical infill panel.

Based on a nonlinear finite element model of the infill panel, Hashemi and Mosalam indicated that there is an interaction between IP and OOP capacities. In that study the interaction was expressed as the *P*-*M* interaction curve of typical infill panel, as shown in Figure 2. The function was expressed as a third-degree polynomial, as shown in following:

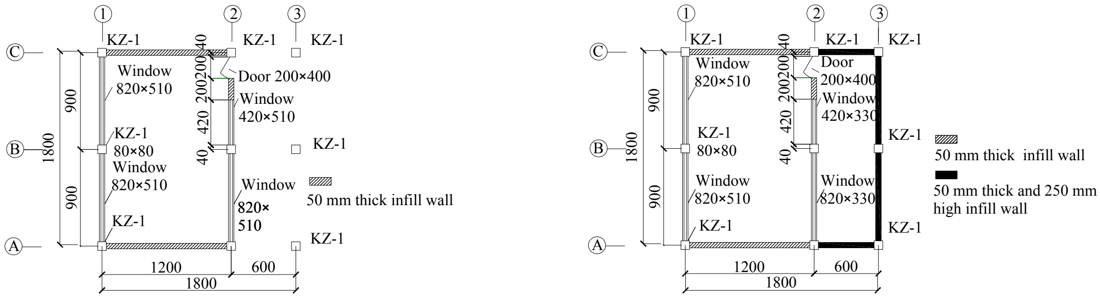
$$\left(\frac{M_{\mathrm{N}}}{M_{\mathrm{N0}}}\right)^{\frac{3}{2}}+\left(\frac{P_{\mathrm{H}}}{P_{\mathrm{H0}}}\right)^{\frac{3}{2}}\leq 1.0 \quad (1)$$

where, M_{N} is the OOP bending strength in the presence of IP force, and M_{N0} is the OOP bending strength without IP force. P_{H} is the IP capacity in the presence of OOP force, and P_{H0} is the IP capacity without OOP force.

3 VALIDATION OF THE INFILL WALL MODEL ACCOUNTING FOR IN-PLANE AND OUT-OF-PLANE INTERACTION

3.1 The model structure by shaking table test and its numerical model

The investigated building is a 4-storey gallery-type teaching building of infilled RC frame with 4 storeys and 2 bays, which was designed according to current Chinese seismic design code for the 7 degree of seismic fortification with a peak ground acceleration of 0.10g. The 1/5 scaled model shown in Figure 3 was built for shaking table test. The height of the first story of this model is 780 mm, the height of other storeys are 600 mm.



(a) Ground floor plan (b) Standard floor plan

Figure 3: The shaking table test model of 4-storey RC planar frame structure.

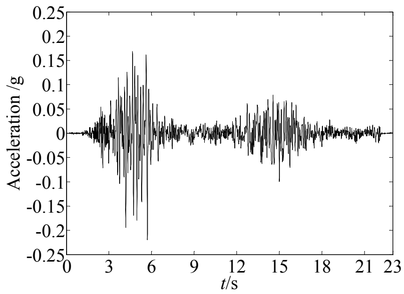


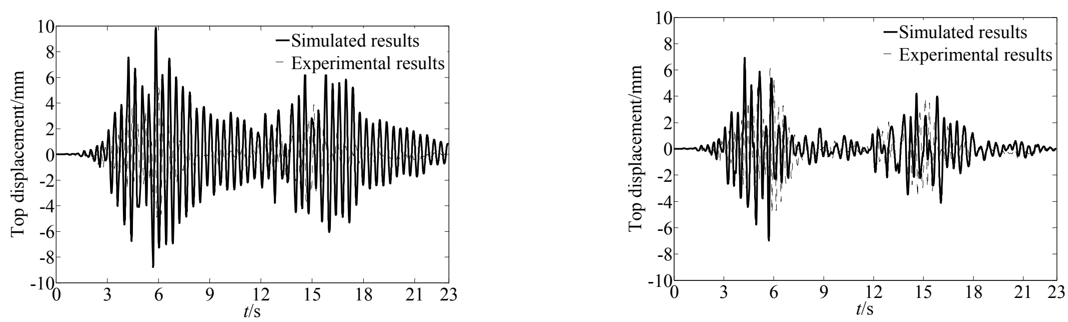
Figure 4: Table excitation of the shaking table test.

The table excitation shown in Figure 4 was taken as input to predict the top displacements. Taking the coincidence degree between stimulating results and test results as evaluation criteria, the error of mean square root, $error_{\text{RMS}} = \sqrt{\frac{1}{N} \times \sum_{i=1}^{n} \left(F_{\text{comp}_i} - F_{\text{exp}_i} \right)^2}$, was used to judge the numerical results .

The numerical model was modeled via OpenSees. The beams and columns are modeled using Displacement-Based Beam-Column Element, in which the P-Δ effect of columns are considered by using P-Delta transformation. The hysteretic of beams and columns are modeled through the fiber sections, in which the fiber for reinforcing steels and concrete are defined as ReinforcingSteel constitutive model and Concrete02 constitutive model respectively [8-10]. The beam-column element of relatively stable fiber discretization was used for infilled walls model, and the two beam with hinge elements based on fiber section were applied to consider the IP and OOP interaction of infill walls [7].

3.2 Comparison of test results and numerical simulation results

The time history curves of top displacement from test and numerical simulation with and without considering the IP and OOP interaction of infill walls are shown in Figure 5. The maximum value of top displacement obtained from test is 6.34 mm, the maximum value of top displacement obtained from the model considering the IP and OOP interaction of infill walls is 6.96 mm, and $error_{\text{RMS}} = 1.72$. And the maximum value of top displacement obtained from model without considering the IP and OOP interaction of infill walls is 9.84mm, $error_{\text{RMS}} = 2.83$. The numerical results with considering the IP and OOP interaction of infill walls are more consistent with the test results than without considering the IP and OOP interaction of infill walls. The results indicate that the numerical model considering the IP and OOP interaction of unreinforced masonry infill walls is valid for modeling the infilled RC frame structure.



(a) Without considering the IP and OOP interaction of infill walls

(b) With considering the IP and OOP interaction of infill walls

Figure 5: Comparison of the top displacement curves.

4 EVALUATION OF COLLAPSE RESISTANCE CAPACITY WITH CONSIDERING IN-PLANE AND OUT-OF-PLANE INTERACTION OF INFILL WALLS

4.1 The investigated structures and numerical models

As shown in Figure 6, the investigated structure is a primary school teaching building, a 6-storey infilled reinforced concrete frame, which is located in the region with seismic fortification 8 degree. The height of the first story of this model is 4000 mm, the height of other storeys are 3600 mm. The main objective is to investigate the influence of the IP and

OOP interaction of infill walls on collapse resistance capacity of the structure. Two analytical models were modeled respectively, namely, with and without considering the IP and OOP interaction of infill walls were modeled respectively.

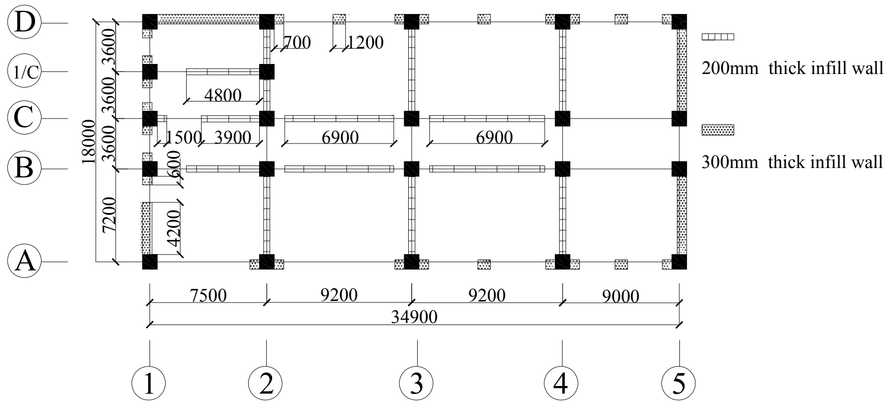


Figure 6: The model of 6-storey infilled RC frame.

The fiber section model is developed via the OpenSees nonlinear analysis software platform. The Displacement-Based Beam-Column Element is used for column and beam component and each component sets five integration points. P-Delta transformation is used as coordinate geometric transformation, which takes into consideration P-Δ effect. The concrete of column and beam section is divided into a certain number of rectangular grids and each grid is assumed to be a fiber. Reinforcing steels are also defined as fibers and is defined by ReinforcingSteel constitutive model [8]. In order to reflect the confinement effect of stirrup, the concrete of column and beam section is divided into cover concrete and core concrete and each is defined by the corresponding constitutive parameters of Concrete02 constitutive model [8-10].

4.2 Nonlinear static analysis of the structure

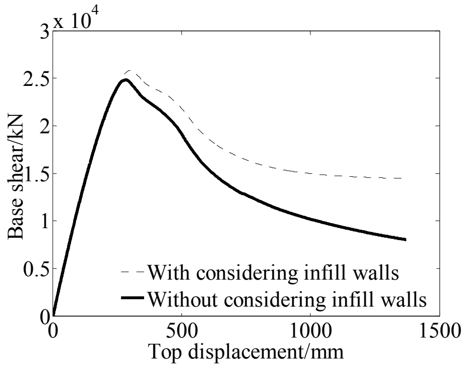


Figure 7: Comparison of pushover curves.

The pushover curves of the two models are shown in Figure 7. When the top displacement is less than 280 mm, the pushover curves obtained from the two models are almost coincident. For the models with and without considering the IP and OOP interaction of infill walls, the models begin to enter yield stage when the top displacement exceeds 300mm and 280 mm respectively. As the increase of top displacement, the curve without considering the IP and OOP interaction of infill walls descends faster than the one with considering the IP and OOP interaction of infill walls. The results demonstrate that without considering the IP and OOP interaction of infill walls, the degradation characteristic of the structure will be underestimated.

4.3 Incremental dynamic analysis of the structure

As shown in Table 1, 22 far field ground motion records from PEER earthquake records database and 2 ground motion records from the Wenchuan Earthquake are selected for incremental dynamic analysis [5, 7].

The IDA curves of two analytical models with and without considering the IP and OOP interaction of infill walls are shown in Figure 8 and Figure 9 respectively. When the maximum interstory drift ratio θ_{max} is less than 0.01, the results from the two models are almost identical. When the maximum interstory drift ratio θ_{max} is between 0.01 and 0.05, the IDA curves become different. Corresponding to the same spectral acceleration $S_a(T_1, 5\%)$, the maximum interstory drift ratio obtained from the analytical model with considering the IP and OOP interaction of infill walls is obvious less than the maximum interstory drift ratio from the analytical model without considering the IP and OOP interaction of infill walls. Therefore, collapse resistance capacity would be underestimated if the IP and OOP interaction of infill walls is not taken into account.

Table 1 Selected ground motion records

No.	Earthquake events			Station	Component
	Name	Magnitude	Year		
1	Northridge, USA	6.7	1994	BeverlyHills-Mulhol	NORTHR/MUL279
2	Northridge, USA	6.7	1994	Canyon Country-WLC	NORTHR/LOS270
3	Duzce, Turkey	7.1	1999	Bolu	DUZCE/BOL090
4	Imperial Valley, USA	6.5	1979	Delta	IMPVALL/H-DLT352
5	Imperial Valley, USA	6.5	1979	EI Centro Array #11	IMPVALL/H-E11230
6	Kobe, Japan	6.9	1995	Nishi-Akashi	KOBE/NIS090
7	Kobe, Japan	6.9	1995	Shin-Osaka	KOBE/SHI090
8	Kocaeli, Turkey	7.5	1999	Duzce	KOCAELI/DZC270
9	Kocaeli, Turkey	7.5	1999	Arcelik	KOCAELI/ARC090
10	Landers, USA	7.3	1992	Yermo Fire Station	LANDERS/YER360
11	Landers, USA	7.3	1992	Coolwater	LANDERS/CLW-TR
12	Loma Prieta, USA	6.9	1989	Gilroy Array #3	LOMAP/GO30090
13	Loma Prieta, USA	6.9	1989	Coyote Lake Dam (SW Abut)	LOMAP/CYC285
14	Superstition Hills, USA	6.5	1987	EI Centro Imp.Co	SUPERST/B-ICC090
15	Superstition Hills, USA	6.5	1987	Poe Road (temp)	SUPERST/B-POE360
16	Cape Mendocino, USA	7.0	1992	Rio Dell Overpass	CAPEMEND/RIO360
17	Chi-Chi, Taiwan	7.6	1999	CHY101	CHICHI/CHY101-N
18	Chi-Chi, Taiwan	7.6	1999	CHY041	CHICHI/CHY041-N
19	Tabas, Iran	7.4	1978	Dayhook	TABAS/DAY-TR
20	San Fernando, USA	6.6	1971	LA-Hollywood Stor	SRERNPEL180
21	Friuli, Italy	6.5	1976	Tolmezzo	FRIULI/A-TMZ270
22	Imperial Valley, USA	7.0	1940	EI Centro Array #9	IMPVALL/I-ELC180
23	Wenchuan, China	8.0	2008	51AXT	EW
24	Wenchuan, China	8.0	2008	51JYZ	EW

The IDA curves of two analytical models with and without considering the IP and OOP interaction of infill walls are shown in Figure 8 and Figure 9 respectively. When the maximum interstory drift ratio θ_{max} is less than 0.01, the results from the two models are almost identical. It indicates that with and without considering the IP and OOP interaction of infill walls can obtain the same seismic response of the structure when the structure remains elastic or the structure is not damaged seriously. When the maximum interstory drift ratio $\theta_{\max}$ is between 0.01 and 0.05, the IDA curves become different. Corresponding to the same spectral acceleration $S_a(T_1,5\%)$, the maximum interstory drift ratio obtained from the analytical model with considering the IP and OOP interaction of infill walls is obvious less than the maximum interstory drift ratio from the analytical model without considering the IP and OOP interaction of infill walls. Therefore, collapse resistance capacity would be underestimated if the IP and OOP interaction of infill walls is not taken into account.

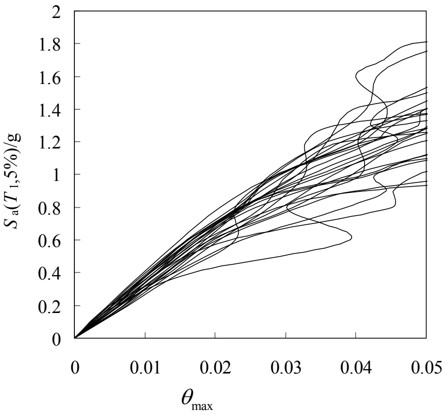


Figure 8: IDA curves without considering the IP and OOP interaction of infill walls.

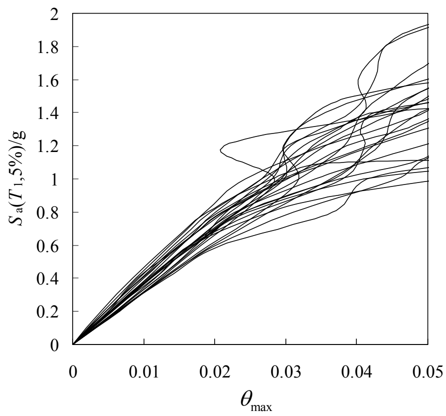


Figure 9: IDA curves with considering the IP and OOP interaction of infill walls.

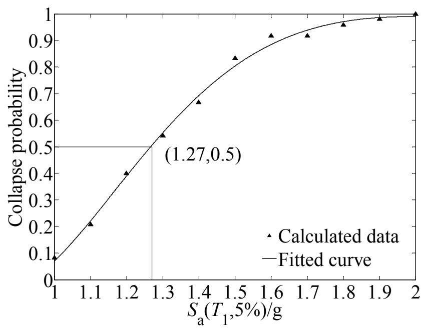


Figure 10: Collapse probability curves without considering the IP and OOP interaction of infill walls.

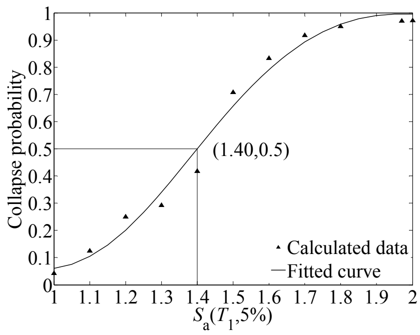


Figure 11: Collapse probability curves with considering the IP and OOP interaction of infill walls.

Taking $S_a(T_1,5\%)$ as random variable, the collapse probability curves without and with considering the IP and OOP interaction of infill walls, which are shown in Figure 10 and Figure 11 respectively, were obtained by using normal distribution parameter estimation. The index $S_a(T_1,5\%)_{50\%\text{Collapse}}$, corresponding to 50% collapse probability, is also shown in Figure 10 and Figure 11. The collapse probability of the model without considering the IP and OOP interaction of infill walls is less than the value of the model with considering the IP and OOP interaction of infill walls. The collapse resistance capacity of the model without considering the IP and OOP interaction of infill walls is $S_a(T_1,5\%)_{50\%\text{Collapse}} = 1.27\text{g}$. For the model with considering the IP and OOP interaction of infill walls, it is $S_a(T_1,5\%)_{50\%\text{Collapse}} = 1.40\text{g}$. It indicates that collapse resistance capacity will be significantly underestimated without considering the IP and OOP interaction of infill walls.

5 CONCLUSIONS

In order to simulate and evaluate the global collapse resistant capacity of structure accurately and reliably, the analytical model should not only consider the characteristics of structural components adequately, but also take into account the behavior of nonstructural components properly. So it is very important to consider the influence of in-plane and out-of-plane interaction of infill walls on the global collapse resistance capacity. The case study results of a three-dimensional model of an infilled 6-storey RC frame teaching building show that global collapse resistance capacity would be significantly underestimated if the in-plane and out-of-plane interaction of infill walls is not taken into account in the analytical model.

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