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COUPLED IN-PLANE AND OUT-OF-PLANE LOADING TESTS ON FULL-SCALE MASONRY INFILLS

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Abstract

A series of six full-scale masonry infills in a single-story one-span reinforced concrete (RC) frame were subjected to monotonic static out-of-plane loading at constant in-plane inter-story drifts. Four of specimens had full-span tie bars anchored in the RC columns as per the latest Chinese seismic design code, whereas the other two had only partial-span tie bars that represented a common practice before the 2008 M8.0 Wenchuan earthquake in China. The pre-imposed constant in-plane inter-story drifts varied from zero to 1% of the story height for different specimens. Airbags were used to apply the out-of-plane pressure on the masonry infills until the collapse of the wall panel. The test results showed a significant reduction in the out-of-plane strength of the masonry infills with the increase of the pre-imposed in-plane drift ratio. Although the full-span tie bars had a considerable effect in increasing the out-of-plane strength of the infills, the extents of reduction in out-of-plane strength for specimens of either full-span or partial-span tie bars were similar. An empirical equation was proposed for the relationship of the out-of-plane strength reduction and the in-plane inter-story drifts. According to the equation, the out-of-plane strength starts to decrease when the in-plane story drift is greater than 0.13% of the story height and is reduced by more than 40% at an in-plane story drift of 0.5%, when the primary RC structure would remain essentially elastic.

Keywords: masonry infill; hollow concrete block; airbag loading; in-plane and out-of-plane interdependency

1. Introduction

Masonry infills in a building are subjected to both in-plane and out-of-plane actions under earthquakes. They are vulnerable to cracking of various extents under an imposed in-plane drift and the cracked masonry panel may exhibit much lower out-of-plane resistance than intact panels. This effect was first investigated by Abrams et al (1996)[1], which focused on the development of the arching action in cracked masonry panels exhibiting out-of-plane deflection. In the last decades, experimental studies on the out-of-plane behavior of crack masonry panels have been conducted both on scaled specimens in the lab [2][3] and on in-site full-scale infills in real buildings[4]. Most experimental tests exerted quasi-static out-of-plane pressure by either airbags or actuators on intact or in-plane cracked infill panels, while dynamic loading tests have also been performed by a uniaxial shake table [5]. Although the equations for the out-of-plane strength of masonry infills based on the arching action theory were confirmed to provide reasonable estimates [6], the reduction effect of prior in-plane damage was derived based on very limited experimental evidence[1]. In recent years, the explicit relationship of in-plane damage and out-of-plane strength of masonry infills has attracted studies by either experimental[8] or numerical simulations[9]. In particular, Dolatshahi et al (2015)[9] revealed by numerical simulation that the reduction in out-of-plane capacity of masonry panels depends significantly on boundary conditions and in-plane damage mode.

Masonry infills are the most commonly-used type of walls for partitions and enclosure of buildings. Recent moderate earthquakes have witnessed the fragility of masonry infills, which exhibited excessive damage prior to substantial structural damage[10]. However, little research effort has been paid on the out-of-plane behavior of masonry infills that conform to the Chinese seismic code[11]. This paper introduces an experimental test on a series of six full-scale masonry infills in a single-story one-span reinforced concrete (RC) frame. Four of specimens had full-span tie bars anchored in the RC columns as per the latest Chinese seismic design code, whereas the other two had only partial-span tie bars that represented a common practice before the 2008 M8.0 Wenchuan earthquake in China. The specimens were subjected to monotonic static out-of-plane loading at constant in-plane inter-story drifts to investigate the effect of in-plane damage on the out-of-plane behavior of masonry infills.

2. Test specimens and loading setup

Each specimen includes a 4500mm by 3700mm masonry panel of concrete hollow blocks and a single-span one-story RC frame that provides the boundary condition. The RC frame was designed according to the Chinese seismic code and represent a typical span in a classroom building for junior and high schools in China. The concrete hollow blocks are nominally 190mm by 190mm by 390mm, and the walls of the blocks are approximately 30mm thick. They are most-commonly used in China nowadays since the fired clay bricks were banned. All seven specimens had the same masonry panels of a height-to-depth ratio of approximately 20.8 and an aspect ratio of 0.82 except that five of them were reinforced by ϕ6 rebars that were anchored in the columns and embedded in the full-span of the mortar beds at an interval of 400mm, whereas the embedded tie bars of the other two specimens extended into the mortar beds for only 1 meter on both sides of the panel (Fig.1). By the configuration of the tie bars, the seven specimens are classified into a full-span-tie-bar series, T-series, and a partial-span-tie-bar series, PT-series (Table 1).

The two columns in each specimen were cast into a monolithic foundation beam which was firmly anchored to the strong floor of the lab by eight bolts of 70mm diameter. A pair of screw jacks were mounted on both sides of the foundation beam to minimize sliding. The specimens were subjected to combined in-plane and out-of-plane loading. In the in-plane direction, we used a 1000kN hydraulic jack to impose a constant lateral drift to the frame. The in-plane lateral drift ratio, R_{IP}, varied from zero to 1% for different specimens (Table 1). The loading jigs on both ends of the RC beam were connected to two pantographs that provided constraints for the out-of-plane degrees of freedom of the jigs. While keeping the in-plane drift, we imposed out-of-plane pressure on the wall panel by inflating three airbags that were placed between the masonry panel and a steel reaction frame. The reaction frame was placed parallel and connected to the RC frame by six ϕ22 steel rods. Hollow load cells were installed between the steel rods and the RC frame to monitor the total force that was exerted on the wall panel (Figs.1 and 2).

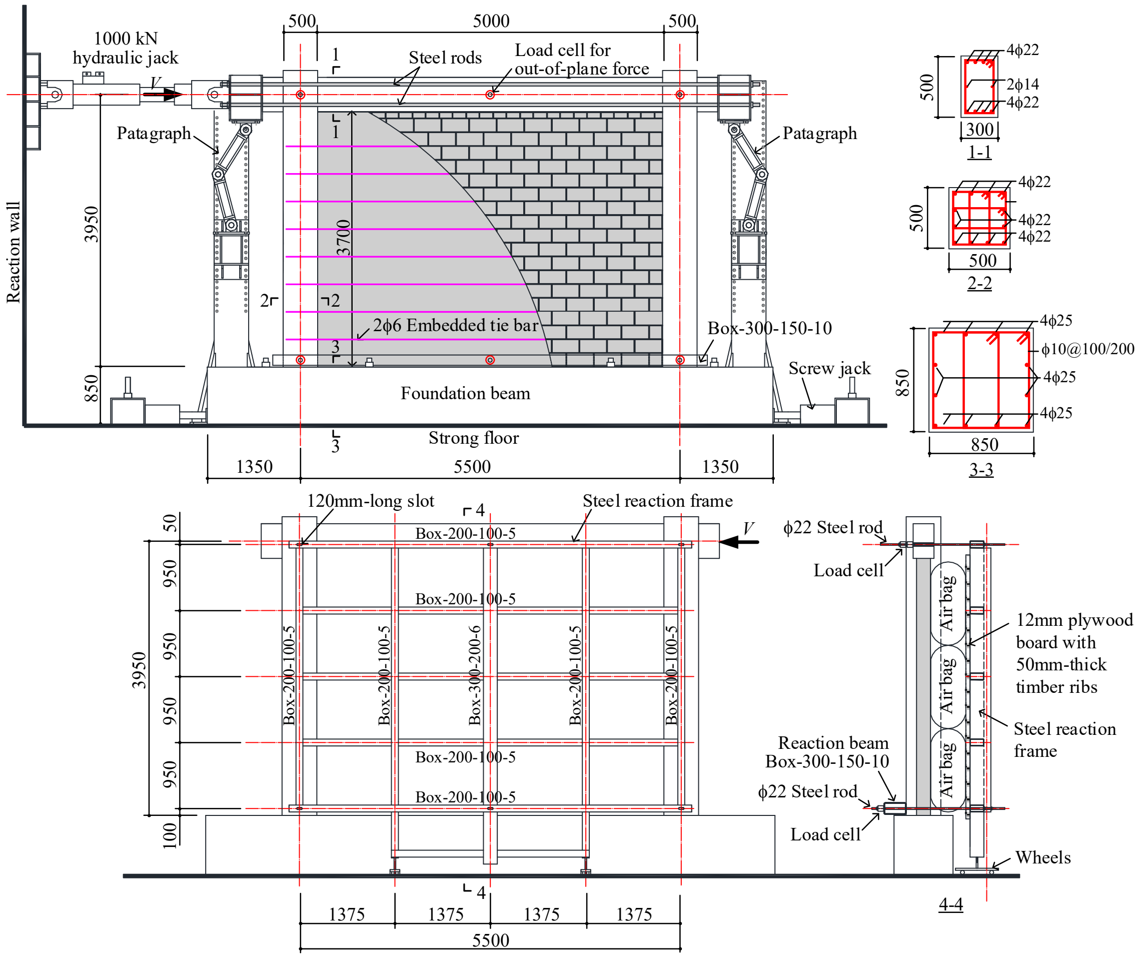
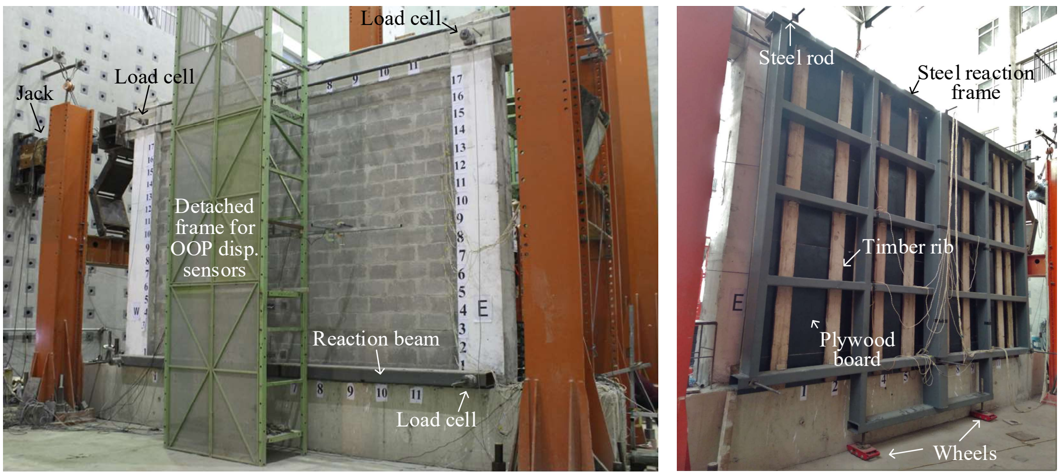


Fig. 1 – Specimens and in-plane out-of-plane loading setup



Front view Back view

Fig. 2 – Photos of test setup

Four displacement sensors, Δ_1 to Δ_4 were used to monitor the in-plane deformation of the RC frame (Fig.3). The in-plane drift ratio, R_{IP}, is calculated by Eq. (1). Another seven displacement sensors, δ_1 to δ_6 and δ_c, were used to capture the out-of-plane deformation and its distribution of the masonry panel (Fig.3), in which δ_c is the out-of-plane deflection at the center of the masonry panel.

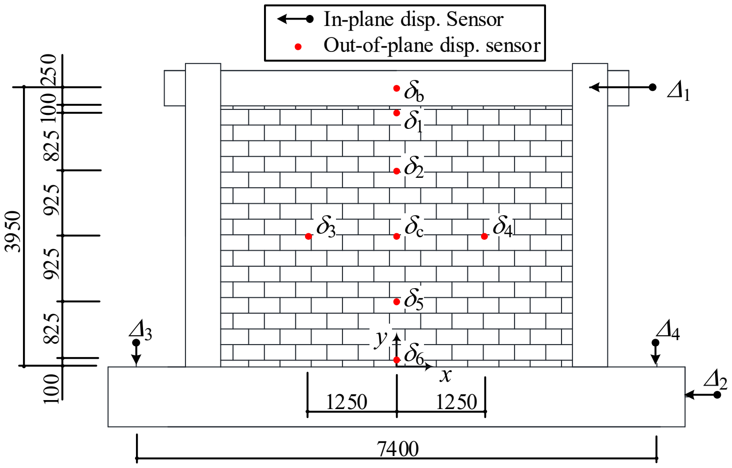


Fig. 3 – Measurements

$$R_{IP} = \Delta_1 - \Delta_2 - \frac{3950}{7400}(\Delta_3 - \Delta_4) \tag{1}$$

3. Test results

By normalizing the out-of-plane deflection at different locations of the wall panel δ by that at the center δ_c, Fig. 4 depicts the distributions of the out-of-plane deflection of the infills in both the vertical (y) and horizontal (x) directions. For the specimens with full span tie bars, the maximum out-of-plane deflection generally took place at the center of the panel, whereas the deflection reached the maximum at the top for partial tie bar specimens. The distributions also support the assumption of two-way arching action over the one-way arching.

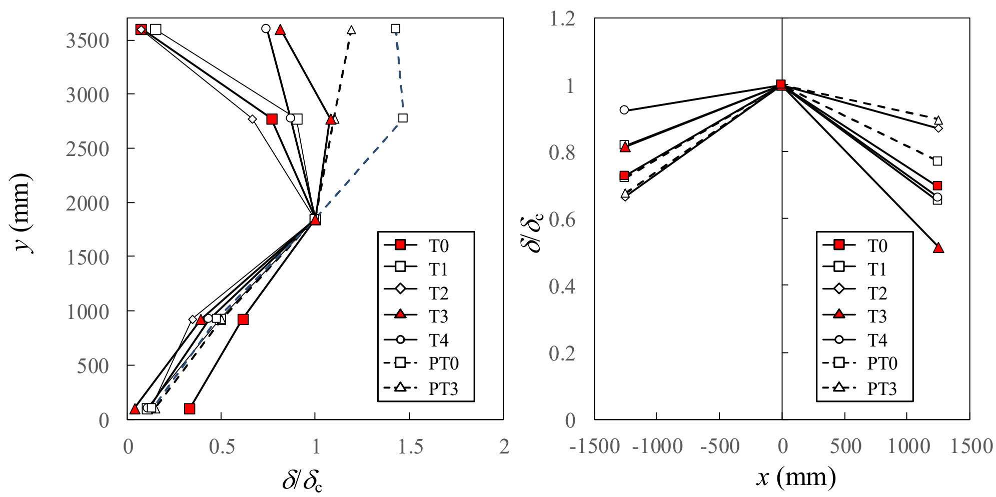


Fig. 4 – Out-of-plane displacement profile of specimens

The out-of-plane strength F_{max} and initial stiffness k_0 of the specimens are listed in Table 2, where F_{max} is the maximum total force of the six load cells. The prior in-plane drift has a significant effect on the out-of-plane strength of the masonry panel. The out-of-plane strength at a 1% in-plane drift ratio (Specimen T4) is less than half of the strength of Specimen T0 which sustained no in-plane damage. On the other hand, the test results suggest no clear effect of R_{IP} on the out-of-plane stiffness. If the abnormally high stiffness of Specimen T1 is excluded, all other specimens exhibited similar k_0 of approximately 4 kN/mm.

Table 2 – Test results of out-of-plane properties of specimens

Specimen ID	T0	T1	T2	T3	T4	PT0	PT3
Measured R_{IP} (%)	0	0.150	0.212	0.509	1.074	0	0.508
OOP strength, F_{max} (kN)	43.0	44.6	33.4	22.6	19.8	27.9	16.1
OOP initial stiffness, k_0 (kN/mm)	3.2	9.9	4.2	4.0	4.4	4.2	4.6

The relationship of the total out-of-plane force F_{OOP} and the out-of-plane deflection at the center δ_c of all specimens was compared in Fig. 5. The out-of-plane load-deflection curves exhibited no sudden drop of force which usually accompanies a brittle failure. Instead, the loss of out-of-plane strength for most specimens was gradual and thus ductile, although the masonry panels were only lightly reinforced.

The configuration of the tie bars has a significant effect on the out-of-plane strength no matter if prior in-plane damage is present or not. For specimens without prior in-plane damage, the out-of-plane strength of the specimen with full-span tie bars (T0) was 54% higher than that of the specimen with partial-span tie bar (PT0). For specimens of R_{IP}=0.5%, the out-of-plane strength of T3 was 37% higher than that of PT3 (Table 2, Fig.5b).

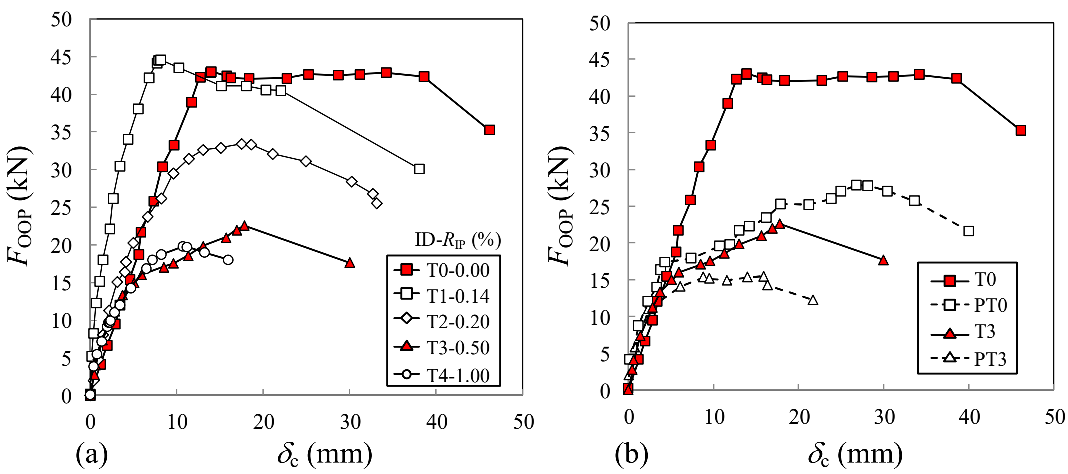


Fig. 5 – Deformed shapes and cracking prior to out-of-plane collapse of specimens: (a) T3 (R_{IP}=0.5%) and (b) T4 (R_{IP}=1.0%)

4. Relationship of out-of-plane strength reduction and in-plane inter-story drift

A reduction factor β is defined as the ratio of the out-of-plane strength of masonry infills with and without prior in-plane damage. The level of prior in-plane damage is represented by the in-plane drift ratio R_{IP} in the current. By plotting the reduction factors β against the respective R_{IP} in the same graph, it is evident that prior in-plane damage caused a significant reduction in the out-of-plane strength of the masonry panel when R_{IP} exceeded a certain threshold (Fig.6). In addition, despite the difference in their out-of-plane strengths, the specimens with full-span and partial-span tie exhibited almost the same trend of strength reduction with respect to R_{IP}.

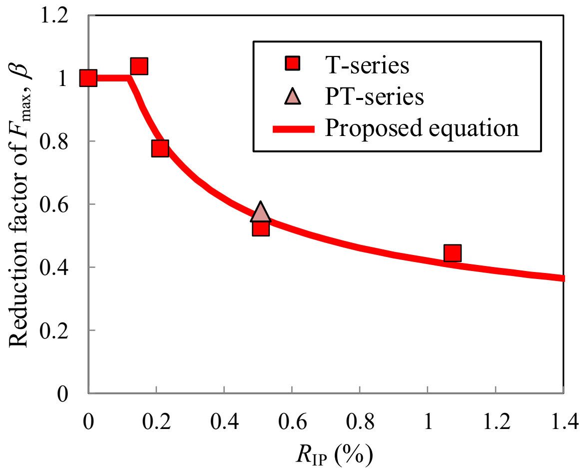


Fig. 6 – Relationship of in-plane inter-story drift, R_{IP}, and out-of-plane strength reduction factor, β.

An exponential equation with an upper bound of unity [Eq. (2)] is proposed to describe the β-R_{IP} relationship shown in Fig. 6. According to the equation, the out-of-plane strength starts to decrease when the in-plane story drift is greater than 0.13% of the story height and is reduced by more than 40% at an in-plane story drift of 0.5%, when the primary RC structure would remain essentially elastic.

$$\beta = 0.42 \cdot R_{IP}^{-0.42} \leq 1 \tag{2}$$

where R_{IP} is the maximum in-plane inter-story drift and is in the unit of %.

5. Conclusions

A series of six full-scale masonry infills in a single-story one-span reinforced concrete (RC) frame were subjected to monotonic static out-of-plane loading at constant in-plane inter-story drifts. The following conclusions can be drawn from the test results.

(1) The masonry panels with full-span tie bars in the test, which were of a height-to-depth ratio of 20.8 and an aspect ratio of 0.82, developed a two-way arching action under out-of-plane surface pressure, regardless of whether prior in-plane damage was present or not.

(2) Prior in-plane drift has a significant reduction effect on the out-of-plane strength of the masonry infills no matter if the tie bars extended for the full-span or not. However, the effect of the in-plane drift on the out-of-plane stiffness was not clear.

(3) An exponential equation with an upper bound of unity is proposed to describe the relationship of out-of-plane strength reduction and prior in-plane drift ratio. The equation suggests a 0.13% threshold for the in-plane drift ratio to reduce the out-of-plane strength and more than 40% reduction in out-of-plane strength at an in-plane drift of 0.5%.

It is worth noting that the specific results were derived from the test results of the current test on masonry infills of very limited variation of parameters. They should be used with cautions if the masonry infills are substantial different from those in the specimens of the current tests.

6. Acknowledgements

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7. References

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