EXPERIMENTAL STUDIES

Although masonry infills have been used largely as architectural components, it has been found that placing masonry inside a reinforced concrete (RC) frame greatly influences the structure's behavior during an earthquake. The masonry infill substantially increases the strength and stiffness in RC frames. However, as a result of this increased stiffness, the presence of masonry infill also increases the seismic demand on the frames. In addition, brittle failure of infill walls can create vulnerabilities such as "soft stories" and "weak stories". Moreover, the interaction of infill panels with the surrounding frame can result in the shear failure of beams and columns, often leading to a loss of vertical load carrying capacity. Many researchers have investigated both the In-plane (IP) and Out-of-Plane (OOP) response in the past few decades, in an effort to understand better the behavior of these RC infill frames. This e-document summarizes some of this extensive experimental research.

In-plane Loading Experiments

Infill Panel Level (Single Story, Single Bay) Studies

Research has been conducted on infill walls using various experimental methods that include monotonic loading, cyclic loading, shake table tests and hybrid simulations. Most experimental studies have used single-story, single-bay specimens under monotonic or cyclic lateral loading. Benjamin and Williams (1958a, b), Holmes (1963), Stafford-Smith (1968), Moghaddam and Dowling (1987), Dawe et al. (1989), Mander et al. (1993), Mehrabi et al. (1994), Negro and Verzeletti (1996), Durrani and Haider (1996), Pires et al. (1998) and Fardis et al. (1999) are among the researchers who have contributed to such studies.

Monotonic Loading

Testing of infill frames began with monotonic loading. The earliest attempt to perform static experiments on infill frames with monotonically increasing lateral load took place in 1952 (Thomas). Since that time, several researchers (e.g., Benjamin and Williams (1957, 1958a, b), Wood (1958), Sachanski (1960), Holmes (1961, 1963), Stafford-Smith (1962, 1966, 1968), Mallick and Severn (1967), Polyakov (1967) and Zarnic and Tomazevic (1985)) have performed experiments on steel or RC frames infilled with different materials such as mortar, bricks, clinker blocks, hollow, grouted, or RC block masonry and clay blocks.

Fiorato et al. (1970) tested several 1/8 scale, masonry brick infill non-ductile frames and concluded that the infill added significant stiffness and strength to the frames but caused a decrease in their ductility.

In the early 1980s, the University of New Brunswick conducted one of the most intensive experimental test programs on monotonically loaded infilled frames. In this program, McBride (1984), Yong (1984), Amos (1985), Richardson (1986) and other researchers examined the frame infill interface conditions, column to infill ties, initial gaps, frame connection types, infill openings, reinforced bond beams, and loading conditions of 34 full-scale single-bay, single-story steel frames infilled with concrete masonry. The experimental results were further evaluated by Pook et al. (1986), and Dawe and Seah (1989).

Al-Chaar et al. (2002) conducted monotonic load tests on five 1/2 scale, single story, non-ductile infill frames with one, two and three bays. Observed results were similar to those of the earlier investigations, with the infill adding strength and stiffness to the bare frames. Important information about the behavior and failure modes of the infill frames was obtained from such experiments. These experiments provided the force-deformation relationships and offered insights into determining the effect of infills on the lateral strength and stiffness of infill frames. In the 1970s and 1980s, more interest was directed toward the numerical modeling of infill frames. Experiments were performed on monotonically loaded frames to reveal the effect of specific parameters such as openings, the contact length between infill walls and bounding frame members, and the size and arrangement of initial gaps.

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Cyclic Loading, Harmonic Excitation, and Shake Table Tests

Cyclic loading experiments were conducted to evaluate the behavior of infill frames under load reversals. Esteva (1966) conducted the first cyclic test on infill frames. Since then, extensive research has been conducted on the cyclic testing of infill frames (e.g. Mallick and Severn (1968), Chandrasekaran and Chandra (1970), Dawson (1972), Leuchars and Scrivener (1975), Klinger and Bertero (1976), Kahn and Hanson (1979), Lian et al. (1980), Parducci and Mezzi (1980), Brokken and Bertero (1981), Zarnic and Tomazevic (1984, 1985, 1988), Yanev and McNiven (1985), Schmidt (1989), Angel et al. (1994) and Mestas (1994)). Summary information on some of these tests follows.

Valiasis and Stylianidis (1989) tested 24 specimens of 1/3 scale single-bay, single-story infilled reinforced concrete ductile frame models under cyclic horizontal loading. Tested infills were unreinforced masonry and were not connected to the bounding frames (i.e. nonintegral infill walls).

To determine the importance of scale effect, Manos et al. (1993) also tested 1/3 and 1/9 scale similar single-bay, single-story URM infilled RC frames with nonintegral infill walls under cyclic loading. The researchers concluded that despite some discrepancies, the general cyclic behavior of URM infilled RC frames could be satisfactorily simulated using small-scale models.

Mehrabi et al. (1994) tested 14 half-scale RC frames infilled with concrete block masonry, in order to evaluate the influence on the performance of the frames of: (1) the strength and stiffness of an infill wall relative to those of the bounding frame; (2) the panel aspect ratio; (3) the lateral load history; (4) the adjacent infill bays; and (5) the magnitude and distribution of vertical loads. The researchers concluded that the infill panels significantly enhanced the load resistance capacities of RC frames. More specifically, they found that the strong panels provided better energy-dissipation capacity for stronger frames. Three different failure modes were observed. In weak panels, slip took place along the bed joints of the panels and the plastic hinges formed in the frame. Columns of the frame failed in brittle shear failure mode for both weak frame and strong panels. Crushing of infills was the failure mode observed for the strong frame/strong panels configuration. The researchers also observed that the specimens subjected to cyclic loading showed lower resistance and faster degradation than those subjected to monotonic loading. One additional observation was an increase in strength with increasing vertical load. However, the influence of the distribution of vertical load between the columns and the beams was insignificant.

Dawe et al. (1989) tested 10 portal steel frames with and without infills of solid clay bricks, in order to evaluate the dynamic stiffness and strength of the structure, the effect of ground motion intensity on the wall degradation behavior, the role of enclosing frame stiffness and column-to-roof rotational rigidity. They concluded that the single-degree-of-freedom model can predict the linear response of infill frames, while the linear and the initial stages of the nonlinear response of these frames can be predicted using the braced frame model.

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Building and System Level (Multiple Stories, Multiple Bays) Studies

Experimental studies have also been conducted in which monotonic and cyclic loadings are applied on multiple-story, multiple-bay infilled frames (e.g. Liauw and Kwan (1985a), Gergely et al. (1994), Mosalam (1996a, b) and Mosalam et al. (1997a, b and 1998)).

Bertero and Brokken (1983) conducted an experimental and analytical investigation of the effects of masonry infill on concrete frames. Quasi-static cyclic and monotonic load tests were performed on 1/3 scale models of the lower 3-1/2 stories of an 11 story, 3 bay reinforced concrete frame infilled in the outer two bays. The researchers found that the infill frames not only modified the available stiffness, strength, damping, hysteretic behavior and deformation capacity of the building: they also modified the demands for a given earthquake. Infill frames were found to increase stiffness, lateral strength and design forces. The authors of this study concluded that URM infill should not be used in non-ductile frames, unless the building can resist elastically the effect of the most severe earthquake ground motion.

Subsequent experimental programs carried out quasi-static testing of infilled frames. Liauw and Kwan (1985a) tested small-scale models of four story infilled frames by applying harmonic load at the top of the frames. They investigated the effect of connection between the infill wall and the bounding frame by testing non-integral (i.e., no connecters at the frame/infill wall interface), partially integral (i.e., connecters along the beam/infill wall interface only), and integral (i.e., connecters around the entire frame/infill wall interface) infill wall types. They concluded that the integral type is stiffer, stronger, more ductile and less degrading than other types and thus, has much larger energy dissipation capacity than do other types.

Manos et al. (1990) tested reduced scale models of two story RC frames infilled with solid clay bricks using several loading techniques; these included static tilt, low level impulse loading on either the first or the second story level, and sweep and simulated earthquake excitations. The researchers observed that the addition of masonry infill walls significantly influenced the seismic response of the structures. They also observed that wide door openings in the second story have little effect on the structure's seismic response for low to medium level simulated earthquake excitations.

Cyclic tests conducted by Mosalam et al. (1997) on multiple story, multiple bay infilled frames with hollow concrete blocks aimed to determine the effects on behavior of the number of bays, the relative strength between the concrete blocks and the mortar joints, and the configuration of openings. The researchers observed that weak blocks lead to corner crushing, whereas stronger blocks lead to mortar cracking, and that the capacity of the infilled frames is not significantly affected by this change of failure type. They also observed that the number of infilled bays affected strength more than stiffness. The researchers concluded that openings in infill walls result in more ductile behavior and a larger ratio of post-cracking stiffness to initial stiffness. The reduction in initial stiffness due to the presence of openings was observed to be approximately 40%. The ultimate load capacities of the solid infills and the infills with windows were found to be similar. It was also observed from strain measurements that compressive stresses predominated along one of the diagonals of an infill wall, which validated the compression-only strut mechanism. Finally, the relationship between the strains along the diagonals of the infill walls and the applied stresses was found to be almost linear, indicating the validity of the equivalent strut analogy.

Hybrid Simulations

Hybrid simulation is a testing procedure that combines static testing with the traditional numerical integration of the governing equations of motion. In its explicit form, the parameters required to conduct the numerical integration are the mass and damping matrices, the restoring force vector and the forcing function. In hybrid simulation, mass and damping matrices, the forcing functions and some portions of the restoring force mechanism are first defined numerically. The specimen is then tested monotonically in each integration step in order to experimentally obtain the remaining part of the restoring force vector. This is done by statically imposing the displacements obtained from the numerical integration to the test specimen. It should be noted that a special case of hybrid simulation occurs, when no portion of the restoring force mechanism is defined numerically, and the test specimen is the only source that provides restoring force. During the test, actual displacements and restoring forces are measured using equipment normally used for static experiments.

A second phase of the Mosalam et al.'s study discussed above involved hybrid simulation tests of multi-bay, multi-story infilled frames. The test results indicated that the presence of infills significantly affected the straining actions in the frame members. The cross sections of the frame members with maximum bending moments were shifted away from beam-to-column connections. This observation indicated that there was a need to include the off-diagonal equivalent struts while modeling the infills. In addition, axial forces in the frame members were predominantly tension, especially for the case of intact walls. An acceptable load path topology was defined from the obtained crack patterns. The researchers concluded that an equivalent dual truss system, connected to the frame members through gap elements, was an appropriate idealization for the masonry infills.

Negro and Verzeletti (1996) conducted hybrid simulation tests on a full scale four story reinforced concrete bare frame, as well as two other frames with different infill configurations. The researchers again found that the presence of infill changed the response of the structure to a large extent. They also found that the irregularities in the panels resulted in unacceptably severe damage to the frame.

Buonopane and White (1999) likewise conducted hybrid simulation tests on infill concrete frames. They tested a half scale two story, two bay reinforced concrete infill frame with window openings in the second story. Observed failure mechanisms included diagonal cracking in the upper story and bed joint shear cracking in the lower story.

As mentioned in "Repair and Retrofit" e-document, Kurt et al. (2012) used the hybrid simulation method to achieve a realistic evaluation of the effectiveness of different retrofit methods, by conducting tests on a 1/2 scale, two story, three bay, low rise infilled RC building in as-built, CFRP retrofitted and precast concrete panel retrofitted cases.

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Shake Table Tests

A limited number of shake table experiments have been performed on infilled frame structures. Fardis et al. (1999) performed shake table tests on single bay, two story RC frames with eccentric (i.e., non-symmetric in plan) arrangement of masonry infills, subjected to bidirectional ground acceleration. This study focused on the effects of the eccentricity on displacement demands on the corner columns.

Zarnic et al. (2001) performed two shake table tests on 1/4 scale, one and two story RC frames with strong block, weak mortar masonry infill walls subjected to unidirectional sinusoidal motion at the base of the structure.

Dolce et al. (2005) performed shake table tests on two dimensional (2D), 1/3.3 scale, three story, two bay RC frames designed for low seismicity regions with and without masonry infill, and with two different types of energy dissipating and recentering braces. The study compared the overall response and the dynamic properties of the tested frames, when subjected to a sequence of artificially generated accelerograms with increasing intensities. These experiments and others were mostly performed on small-scale models, due to the size limitations of the shaking tables. They focused on different aspects of the seismic behavior of infilled frames, one of them being the torsion effects due to the eccentric arrangements of the infill walls.

In recent years, experimental investigations involving shake table testing of infill frames have been conducted by Lee and Woo (2002) and Hashemi and Mosalam (2006), among others. Lee and Woo (2002) conducted shake table tests on two 1/5 scale, two bay, three story concrete frames with non-seismic detailing. One frame was a bare concrete frame; the other had masonry infill. It was found that the infill contributed about 80% of the global capacity and about 85% of the stiffness. The failure mode in the bare frame was the formation of a “soft story” mechanism. For the infill frame, it was bed-joint shear failure.

Hashemi and Mosalam (2006) tested a 3/4 scale model of the first story and middle bays of a five story infill frame structure. In addition to the beams and columns of the RC frames, the specimen also included the first floor slab. The experimental study was used to calibrate analytical models that were being developed by the same investigators. Hashemi and Mosalam found that that the infill wall increased the stiffness of the test structure by a factor of 3.8, shortened the natural period by approximately 50%, increased the damping coefficient (depending on the level of shaking) from 4-12%, and increased the energy dissipated by the system.

Experimental investigations on the performance of infill frames under lateral loads have been also carried out by Murty and Jain (2000), Canbay et al. (2003) and others.

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Out-of-Plane Tests

An important aspect of the behavior of infill frames is the performance of the masonry infill under out-of-plane (OOP) loads. Premature out-of-plane failure of infill panels can result in the development of undesirable failure mechanisms, such as the "soft story" and the short column effects. In addition, out-of-plane failure results in falling debris, which is a threat to life safety.

Angel et al. (1994) carried out a study to determine the out-of-plane behavior of URM panels that have been damaged by in-plane loads. Eight large scale single bay, single story infill frames were first subjected to in-plane load reversals, in order to create a pre-existing damaged state. This was followed by out-of-plane testing of the cracked/damaged specimen. The study found that the out-of-plane strength was reduced by a factor of two, as a result of the pre-existing cracking. Despite this, infill panels were found to have a significant out-of-plane strength due to the development of an arching action. The extent of the arching action was dependent upon the slenderness ratio of the panel and the masonry compressive strength. A simple equation was developed to estimate the panel out-of-plane strength, based on its slenderness ratio and the masonry strength.

Felice and Giannini (2001) investigated the out-of-plane behavior of infill panels, specifically evaluating the influence of connection to transverse walls. The investigation aimed to develop an analytical expression that could be used to evaluate out-of-plane resistance of the infill panel based on geometry and the strength of the masonry. The researchers concluded that there was a decrease in the out-of-plane resistance with decreasing size and strength of masonry units.

Limited experimental research results are available on the interaction between the IP and the OOP behaviors of the URM infill walls. Flanagan and Bennett (1999) conducted a set of experiments that consisted of a series of IP, OOP, and combined IP/OOP loadings for a single story, single bay clay tile infilled RC frame. Three combined loading experiments were conducted. In the first, loading was applied in the IP direction up to a certain value; then, after removing the IP load, OOP pressure was applied until failure. In the second experiment, loading was applied in the OOP direction up to a certain value; then, after removing the OOP load, the IP force was applied until failure. The third experiment consisted of loading simultaneously in the IP and OOP directions by holding the IP deformation and applying the OOP pressure until failure. Although the results did not show strong interaction when the orthogonal loads were applied sequentially, strong interaction was observed when the infilled frame was subjected to simultaneous application of IP and OOP forces. Results showed a 42% drop in the IP capacity of the infill wall, when it was subjected to OOP pressure equal to 57% of its capacity.

Selected References

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