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SEISMIC RESPONSE OF R/C FRAMES WITH UNREINFORCED MASONRY INFILLS

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ABSTRACT

The seismic response of reinforced concrete frames with unreinforced masonry infills is studied by testing four near full-scale, singly-bay subassemblies under in-plane reversed cyclic loading. The frame stiffness and opening aspect ratio were varied by changing the sizes of the beams and columns, and by varying the width of the opening, respectively. The subassemblies were first tested without infills up to a drift level of 1% and then retested after placing masonry infills up to a drift of 3%. The response of the infill is then deduced from the observed response of the virgin and the infilled frames. The effect of the panel aspect ratio and the stiffness of the infill relative to the frame are discussed in terms of stiffness, strength, energy dissipation and failure mode.

KEYWORDS

Reinforced concrete; masonry infills; earthquake response; moment-resisting frames; in-plane loading.

INTRODUCTION

Masonry infills in framed structures have been used extensively as interior partition walls and exterior claddings without accounting for their structural action in resisting lateral loads. The presence of masonry infills in framed structures significantly modifies the structural response to strong ground motion. The interactive behavior is complex and cannot be quantified easily. Due to the lack of simple analytical models and the uncertainty due to the large number of variables involved, the contribution of masonry infills is commonly disregarded in conventional design practice. However, this practice has been questioned over time and studies made to investigate the contribution of infills and incorporate it in the design of new buildings and the evaluation of existing ones. The abundance of such framed structures with unreinforced masonry infills in earthquake prone areas necessitates that further effort be directed towards developing an understanding of the behavior of such infills under repeated in-plane and out-of-plane cyclic loading

Over the last four decades considerable research (Klingner and Bertero, 1978) has been conducted to study the behavior of infilled frames. Most investigators tested specimens under monotonic loading and studied a variety of parameters. However, little data are available regarding the cyclic behavior of infilled frames, which relates to seismic performance. Extensive research has been carried out on the static in-plane behavior of masonry infills. The most commonly adopted model was a single story, single bay steel or concrete frame while some data is available on multi-story and multi-bay frames. Infill materials were typically clay brick or concrete block, while hollow clay tile (HCT) has been used occasionally. Some of the parameters studied for the evaluation of infill response are the type of confining frame, the type of masonry unit used for the infill and the relative frame/infill strength. The effect of load on columns, interface condition between infill panel and frame, gaps and panel openings has also been studied. The infill response and mode of failure is predominantly dependent on the strength and stiffness of the confining frame (Dhanasekar, 1986). Weak infills with stiff and strong confining frames deform and crack along with the frame and fail typically by cracking along the loaded diagonal, forming an X-type crack pattern for cyclic loading. In case of weak frame and strong infill, the response is controlled by the infill and there is a possibility for brittle failure.

Previous research (Dawe, J., Schriver, A. and Sofocleous, C., 1989) has established that reduced frame-to-panel interface bond and friction leads to lower initial and ultimate strength as well as wider spread of cracking along the compression diagonal. The initial stiffness is increased by the provision of bond beams at intermediate levels. A gap at panel and roof beam interface results in significant reduction both in the initial stiffness and final strength. Panel openings reduce first crack load but their effect on ultimate strength is minimal. Provision of vertical reinforcement around an opening increases the initial stiffness but does not affect the major cracking load and ultimate strength of the panel.

EXPERIMENTAL PROGRAM

The effect of unreinforced brick masonry infills on the strength and stiffness characteristics of reinforced concrete frames subjected to in-plane cyclic loading was investigated experimentally. Some of the particular objectives were (a) to study how the presence of unreinforced masonry infills modifies the stiffness, strength and energy dissipation characteristics of reinforced concrete frames, (b) to determine the effect of variation in panel aspect ratio on the stiffness, strength and hysteretic characteristics of the masonry infilled frames, and (c) to investigate the effect of variation in frame stiffness relative to the infill, on the in-plane cyclic behavior of unreinforced masonry infills.

In order to achieve these objectives, four one-story, single-bay reinforced concrete frame specimen were tested under in-plane quasi-static cyclic loading up to ±1.0 % drift to determine the load-deformation characteristics of the bare frame.These were later filled in with brick masonry and first tested under similar cyclic loading. The infilled frames were subsequently subjected to cyclic loading of greater drift amplitude (up to ±4.0 %) till failure occurred.

Test Specimens

The confining reinforced concrete frames were designed to be stronger than the masonry panel, so as not to fail either in flexure or shear, before the ultimate strength of the infill was reached. The frame stiffness and opening aspect ratio were varied by changing the sizes of the beams and columns, and by varying the width of the opening, respectively. Table 1 gives the dimensions and other properties of the various frames and Fig. 1 presents the elevation and cross-sections of the members of the frame along with typical reinforcement details.

Masonry Infills

Common clay bricks manufactured locally were used for masonry infills. The perforated brick specimen were tested in accordance with ASTM C-62 and C-67 for initial rate of absorption, water absorption in 24 hours and the flat-wise compressive strength. Single-wythe($3^1/_2$") thick infills were built in all the frame specimen with a slenderness ratio of h/t = 23. Dimensions and shapes of the bricks were uniform. Three types of colored bricks were used but their properties were found to be close enough to justify their random use.

The infills were constructed with Type S mortar with proportions by weight of $1:{}^{1}/_{2}:4^{1}/_{2}$ (cement: lime: sand). Ready mixed masonry cement was used for this purpose. Type S mortar is used commonly for masonry construction when greater mortar strength is desired

Table 1. Frame Properties

Properties	Frame A	Frame B	Frame C	Frame D
Concrete compressive strength f_c' (psi)	4975	5105	5440	5540
Column area A_g (in^2)	100	144	100	144
Column moment of inertia I_g (in^4)	833.3	1728	833.3	1728
Column steel ratio $\rho_s = A_s/A_g$(%)	1.76	1.83	1.76	1.83
Column ties	#3@5"	#3@5"	#3@5"	#3@5"
$(M_u)_{col}$ (k-in)	310	575	312	578
V_u column (k)	26.2	35.1	26.7	35.8
Beam area A_g (in^2)	100	100	100	120
Beam moment of inertia I_g (in^4)	833.3	1728	833.3	1000
Beam top/bottom steel ratio $\rho_s = A_s/bd$ (%)	1.03/1.03	1.03/1.03	1.03/1.03	0.86/0.86
Shear stirrups	#3@5"	#3@5"	#3@5"	#3@5"
$(M_u)_{beam}$ top/bottom (k-in)	310	310	312	315
V_u beam (k)	26.2	26.4	26.7	29.0
Column/Beam flexural capacity $(M_u)_{col} / (M_u)_{beam}$	1.00	1.85	1.00	1.83
Height of opening (in)	81.5	81.5	81.5	81.5
Width of opening (in)	79	75	61	57
Aspect ratio	0.97	0.92	0.75	0.70

Testing Procedure

In-plane lateral load was applied at the end of the top beam along its centroidal axis through a servo-hydraulic actuator as shown in Fig. 2. The tests were conducted under displacement control and load-drift response was obtained for each of the specimen. From each of these plots the initial and residual stiffnesses for the frames were obtained for drift levels up to 1%. The loading sequence consisted of 20 cycles of increasing displacement. The cracked frames were later infilled with unreinforced perforated brick masonry and allowed to cure for about 8 weeks. Each of the specimen was then installed in the test frame and instrumented as described later. The same loading history, as used for bare frames, was applied and load-drift response for infilled frames obtained. The infilled frame specimen were subsequently subjected to several drift cycles of gradually increasing amplitude up to 4% drift. Cycles at certain drift levels were repeated to study the strength and stiffness degradation of the infill specimen.

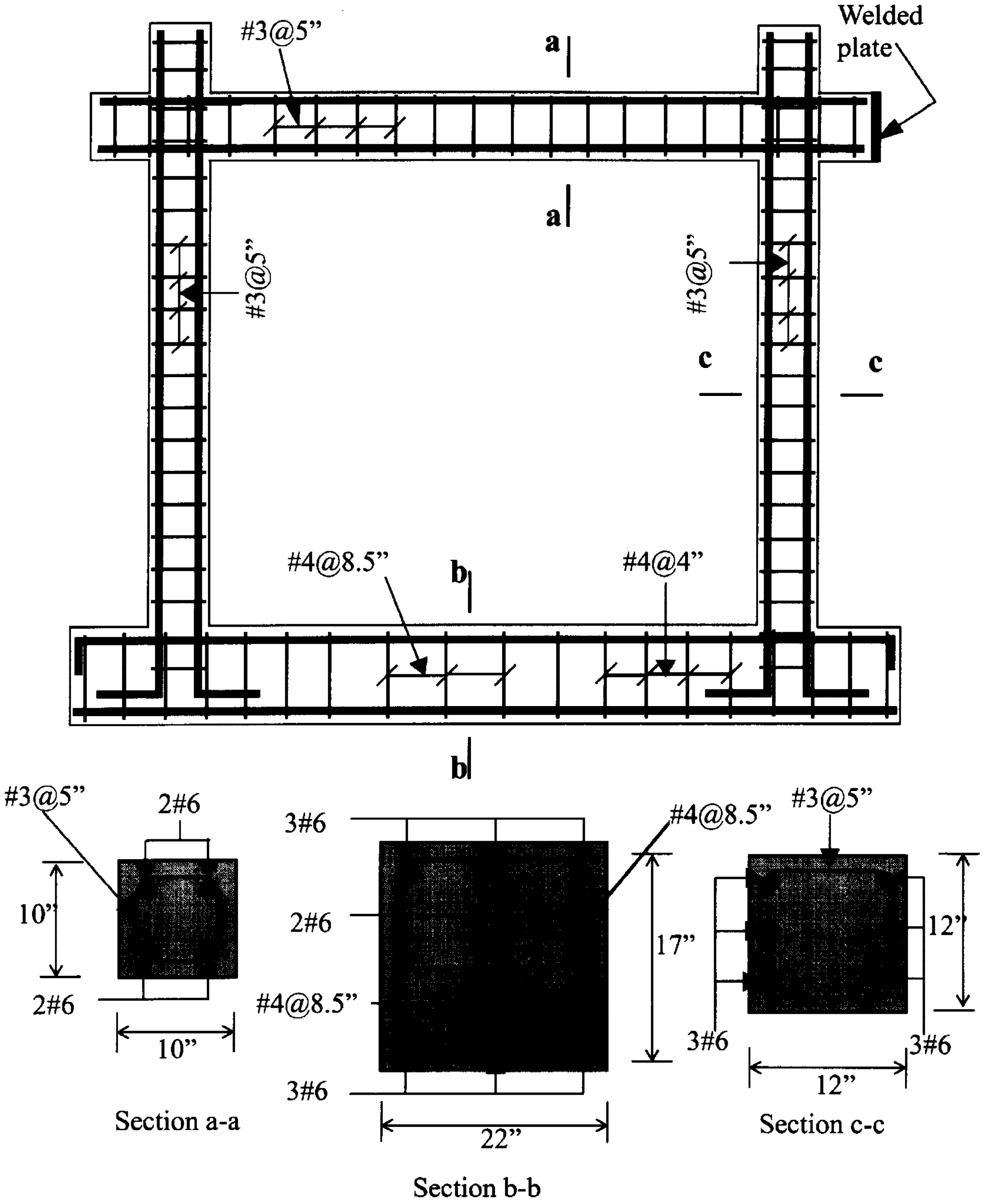

Fig. 1. Reinforcing Detail for Typical Frame Specimen

Instrumentation for the tests consisted of LVDT's and load cells. A high resolution dial gauge was used to monitor the displacement of the base beam due to base slip caused by inadequate anchorage to the reaction frame. The displacement at the top of the column was measured directly through the actuator LVDT since the test was conducted in displacement control mode. The properties of the construction materials used to build the frame as well as those of the bricks and mortar used in the construction of the masonry infills are summarized elsewhere (Haider, 1995). Materials tested included masonry units, masonry prisms, mortar cubes, concrete cylinders, concrete beams, and reinforcing bars. The test samples were built at the time of construction of the frames and infills, and tested at the same time as the infilled frame specimen.

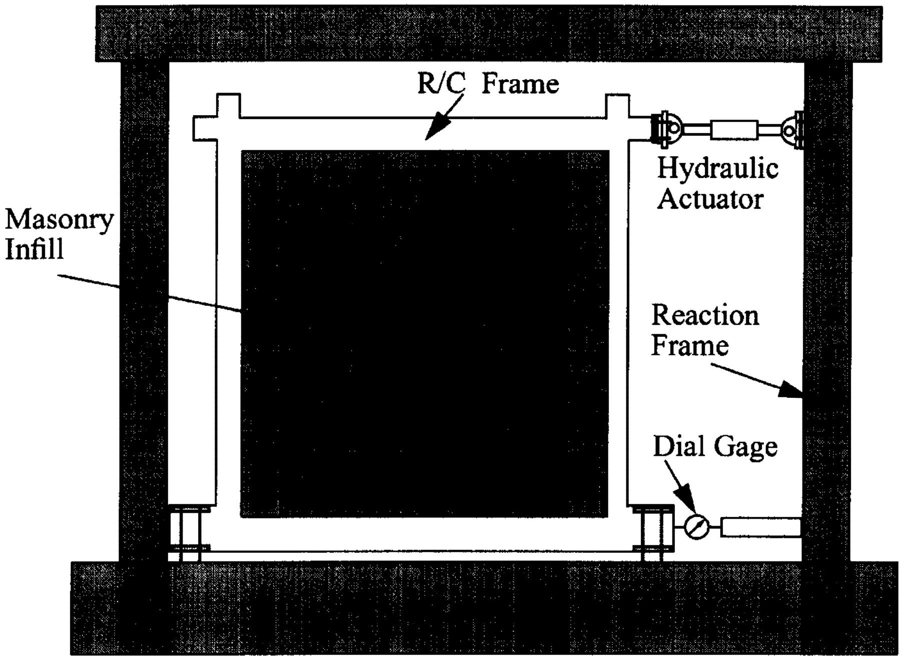

Fig. 2. Test Setup with Infilled Frame Specimen

TEST RESULTS

The frame assemblies were first tested under reversed cyclic loading up to a drift level of ±1.0% and later filled in with the brick masonry and tested again up to a drift level of ±4.0%. At each drift increment the infill was inspected for cracks in the mortar/bricks, and the cracks marked for ease of identification. The lateral forces required to cause cracking of the frames as observed experimentally were nearly 1.2 times the theoretical values. The experimental values of stiffness are much lower than the theoretical ones. The crack patterns resulting from the application of lateral load to infilled frames are shown in Fig. 3. The major cracks developed up to drift levels of 2.5% in either direction are shown. Beyond this drift level no meaningful cracks developed and the infill was so severely damaged that its contribution to the strength and stiffness of the infilled frame became insignificant.

For all the specimen the first diagonal step cracks in the infill originated at the center of the panel where the diagonal tension stresses were the maximum. The first crack appeared at a drift level of 0.5% for loading in either direction. With repeated cycling at the same drift levels the existing cracks widened and extended towards the loaded corners and could easily be seen opening and closing along the compressive diagonal during forward and reverse motion of the specimen. Cracking along the principal diagonal divided the infill panel into two parts, each contributing part of the strength and stiffness furnished by the infill panel as a whole. This led to the formation of further diagonal cracks parallel to the loaded diagonal, and verification of the equivalent diagonal strut action as being representative of the infill behavior. During subsequent testing at larger drift amplitudes, further diagonal cracks developed at a steeper angle to the horizontal. Diagonal cracking was found to be more distributed in case of frames C-2 and D-2 which had an aspect ratio smaller than 1. This observation suggests that the equivalent strut action is less pronounced in case of infills with aspect ratios smaller than 1.

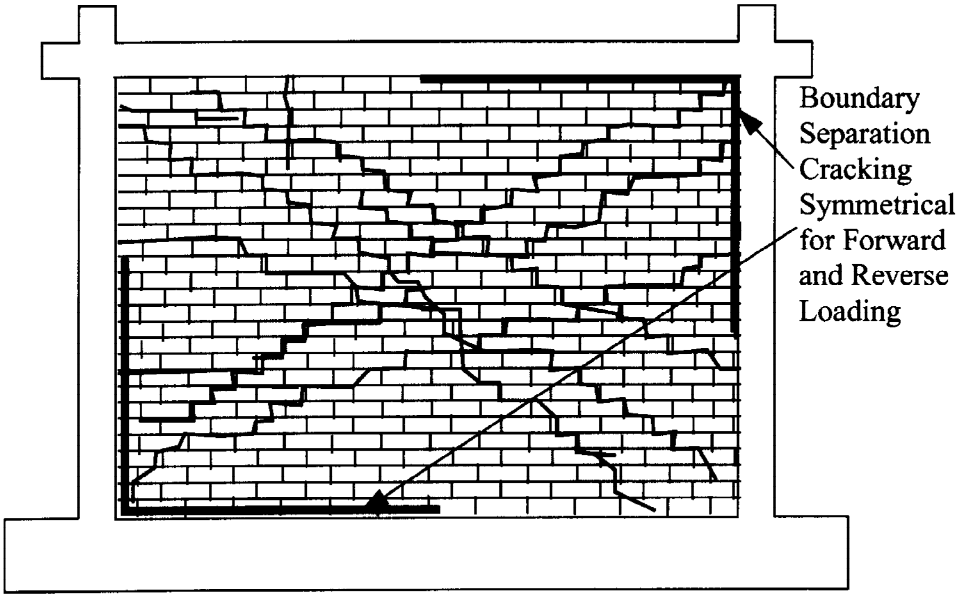

Fig. 3. Crack Pattern for Specimen A-1

In case of infilled frame A-1, horizontal bedding cracks formed at midheight of the panel adjacent to the tension column, at a drift level of 1.0% These cracks were caused by the transfer of tensile stresses from the column to the panel. This was followed by the development of vertical tension cracks in the infill close to the junction of the beam with the compression column, at a drift amplitude of 1.5%. Such cracks define the limit of the secondary compression strut development after the primary diagonal strut has degraded. For this frame the formation of a plastic hinge at the base of the tension column resulted in extensive concrete crushing and the damage being concentrated in that location. The infill remained largely intact at that corner while crushing was observed at other corners of this specimen. The beam-column joints at the top of the tension column for loading in either direction degraded due to a concentration of shear stresses leading to corner crushing at a drift level of 2.0% in case of infilled frame specimen B-1 and D-2.

The failure mode of the specimen provided an interesting insight into the behavior of infilled frames. Final failure was characterized by the formation of plastic hinges at beam-column joints in the frames, extensive cracking of the infill, crushing, loosening and out-of plane fall-out of the core bricks just above and below the intersection of the primary diagonal struts formed by loading in either direction. The fact that high amplitude in-plane drifts resulted in out-of-plane failure leads to the conclusion that the bucking of the infill acting as a compression strut governs the failure of the infilled frame once the compressive strength of the strut has been exceeded and the infill has cracked appreciably.

The hysteretic loops were symmetrical in the forward and reverse directions of loading. There was a progressive increase in the lateral load as the drift level increased. Boundary separation along the frame-infill interface did not result in an appreciable loss of stiffness. The load-drift response was approximately linear up to a drift level of 0.5% in either direction. The stiffness of the frame-infilled assemblage decreased after the onset of the diagonal cracking but the system continued to resist higher loads. The maximum strength was attained, in all cases, corresponding to a drift amplitude of 1.5% except for specimen A-1 in which case it was at 1.0%. The strength and stiffness of the frames for repeated cycles of the same drift amplitudes were found to be smaller than the values at first loading. The hysteretic loops also narrowed with repeated load cycling and consequently less energy was dissipated at second and third cycles.The hysteretic loops of all the infilled frame specimen exhibited pronounced pinching of the loops at the point of load reversal. After the strength capacity of the specimen had been attained, further drift caused crushing in the compression diagonal. The resultant shortening of the diagonal caused one half of the panel to slide outward with respect to the other in the plane of the infill. Friction in the horizontal cracks resulted in greater energy dissipation for the panel as the cracks opened up under load. As load reversal occurred after crushing of the diagonal strut, it caused closure of the vertical cracks opened previously. This closure did not occur immediately and the load-drift response curve exhibited some pinching as a consequence. The only load resistance in this range was contributed by the friction along horizontal cracks and compression at the closed vertical cracks. With repeated cycling the zone of diagonal crushing widened. This increased the shear drift necessary to mobilize strut mechanism leading to an accentuation of the pinching in the load-drift curves. The response characteristics of the infilled frames are summarized in Table 5..

Table 5. Infilled Frame Response Characteristics

Specimen	H_{cr} (k)	Δ_{cr} (in)	f_{cr} (psi)	Max.Force at 1.0% drift H_{1b} (k)	H_u (k)	Δ_u (in)	f_u (psi)
A-1	33.26	0.425	120.27	49.68	49.68	0.859	179.61
B-1	33.87	0.434	129.03	48.86	61.17	1.312	233.04
C-2*	26.89	0.342	125.95	30.70	-	-	-
D-2	51.20	0.803	258.27	51.5	55.22	1.229	276.79
* Test stopped due to base failure							

The stress in the infill was computed by dividing the applied lateral load by the product of panel width and thickness. For all specimen except D-2 the stress at cracking was fairly constant indicating that up to the development of the first diagonal crack the effect of variation in aspect ratio and relative stiffness of infill to frame is minimal for the specimen tested. The ultimate strength of stiffer frame specimen B-1 is nearly 1.3 times the corresponding strength for specimen A-1. This shows that for a 20% increase in the column dimension, the strength of the infilled frames is enhanced appreciably. The strength of frames with lower aspect ratio is greater than that of frames with higher aspect ratio but identical column dimensions. This is borne out by the observation that the ultimate strength of specimen D-2 with a smaller aspect ratio is 1.2 times that for specimen B-1. However, the data is too limited to arrive at generalized conclusions regarding the behavior of infilled frames.

Based on the load drift response of the bare and infilled frame specimen it can be seen that the strength, stiffness and hysteretic energy of the frames are enhanced appreciably in the low drift range of response by the introduction of the masonry infills. This is illustrated by the results presented in Table 6. Subscripts ‘b’ and ‘i’ are used to denote bare and infilled frame specimen respectively

The strength contributed by the confined infill to the overall infilled frame response is, on an average, 60% of the strength of the infilled frame. From the derived hysteresis loops it is observed that the strength and stiffness contribution of the infills is highly significant and it is exceedingly wrong to ignore their effect on the behavior of framed structures. The strength and stiffness degradation due to load cycling is also very prominent and the infill plays a major role in determining the extent of such deterioration. The hysteretic loops are pinched much more severely than for the corresponding bare frames, especially evident in case of specimen D-2. This leads to the conclusion that the pinching effect is mainly contributed by the brittle infill.

Table 6. Comparison of Bare and Infilled Frames at 1.0% drift

Specimen	Strength Ratio H_{1i}/H_{1b}	Stiffness ratio		Cumulative Energy Dissipation Ratio
		Initial Stiffness K_{oi}/K_{ob}	Secant Stiffness K_{1i}/K_{1b}	E_{1i}/E_{1b}
A-1	3.53	3.80	5.52	4.26
B-1	2.25	2.21	3.47	2.99
C-2	2.17	2.71	3.32	2.34
D-2	2.32	1.58	3.48	2.02

CONCLUSIONS

Infilling reinforced concrete frames with unreinforced masonry infills results in significant increases in the strength, stiffness and energy dissipation capacity of the frames under in-plane lateral loading. However, the unreinforced masonry infill is susceptible to out-of-plane fall-out after separation from the bounding frame. If this fall-out is effectively prevented, masonry infills may be used to improve the lateral strength and stiffness of multistory framed structures. Due to the introduction of the infill, the lateral strength of the reinforced concrete frames is increased up to 2.5 times the value for bare frame. The initial stiffness is also enhanced by a similar margin. An increase of up to 4 times is observed in the peak-to-peak stiffnesses for cycles of 1.0% drift amplitude. The infill results in better energy dissipation characteristics especially at higher drift amplitudes when the infill has cracked. Large amounts of hysteretic energy are dissipated through friction across panel cracks and the gradual degradation of the initially high panel strength and stiffness. Infills with stiffer bounding frames develop higher ultimate strengths and exhibit smaller stiffness degradation and better energy dissipation characteristics compared to those with relatively flexible confining frames. A reduction in aspect ratio results in lower strength and less effective energy dissipation while there is no significant effect on the stiffness. The equivalent strut action is also less pronounced for specimen with aspect ratio less than 1.0

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