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ASSESSMENT OF DIAGONAL AND RACKING LOADING OF RC INFILLED FRAMES

A. Dukuze
J.L. Dawe
Atlantic Masonry Research and Advisory Bureau Inc.
University of New Brunswick, Box 4400, Fredericton, NB
Canada, E3B 5A3

Abstract

Similarities between diagonally tested infilled frames and those subjected to racking load were investigated. With the sole parameter being the beam-to-column relative stiffness I_b/I_c, two series comprising fifteen one-third scale models of square infilled frames were fabricated and subjected to in-plane lateral loading. Eleven units were tested diagonally and racking loads were applied on four specimens. Despite different types of loading, specimens exhibited similar behaviour in terms of load vs displacement of the compressed diagonal, strength, stiffness and failure modes. Test results suggest that diagonally tested infilled frames provide a reliable alternative to racking tests.

1 Introduction

As composite systems, the mechanical performances of infilled frames depend on the contribution of both panels and surrounding frames. To investigate the interaction between these components, two main test setups have been used by various investigators throughout the world. These techniques included testing the specimens either loaded diagonally or in racking mode.

There has been speculation on how well a diagonal test may simulate the behaviour of an infilled frame subjected to racking load. Although racking tests were used by researchers including Benjamin and Williams (1958), Polyakov (1960), Fiorato et al.

(1970), Yamada et al. (1974), Dawe and Seah (1989) and Mehrabi et al. (1994), diagonal testing was the most common test setup as adopted by numerous researchers including Stafford Smith (1966), Holmes (1961), Mainstone (1971) and Barua and Mallick (1977). Diagonal setups have been preferred since they require minimum equipment readily available in most structural testing laboratories.

Subjected to lateral loading, the nature of forces transferred to the frame members depends on the test setup. In diagonal tests, the frame members are in compression while windward columns are subjected to bending and tension forces due to racking. However, in real building configurations, actions from upper storeys lead to net compression forces in lower columns. Therefore, both testing setups would yield similar force distributions especially in upper stories of tall buildings as noted by Mainstone (1971).

Examination of the infilled frame performance under lateral loading indicates that masonry panels act as braces by markedly reducing lateral drifts of open frames. Investigations conducted by Stafford Smith (1966) concluded that panels surrounded by frames effectively act as compression diagonal bracing.

In a recent study, an experimental program was undertaken at the University of New Brunswick to investigate the behaviour of reinforced concrete frames infilled with masonry panels. Since most of the specimens were diagonally loaded, a complementary study was conducted to assess the validity of this mode of testing compared to racking tests. This investigation provided information needed to assess the assumption made regarding the similarities of both testing methodologies in terms of infilled frame performance under lateral forces. The overall behaviour, including the load versus displacements curves, the in-plane stiffness and resistance, and the failure modes are reported and discussed.

2 Methods

2.1 Specimen Description

To complement tests conducted on diagonally loaded specimens, racking tests were performed by Dunham (1996) on one-third scale square specimens which differed in the beam-to-column inertia ratio referred to as $\beta = I_b/I_c$. Specimens were tested for values of β of 0.2 ,1 and 5. All the test units were one meter high by one meter long with frame member sizes as shown in Table 1. Since racking tests required the test units to be anchored to the laboratory strong floor, the specimens were provided with very stiff and strong base beams. While at least two specimens were tested for diagonally loaded units, only one specimen per category was tested in racking mode.

All the specimens were cast in horizontal position and raised in upright position thereafter for curing and paneling purposes. Curing consisted of spraying the specimens every twenty four hours for seven days and subsequently covering them in burlap sheets until after twenty eight days. For modeling reasons, a microconcrete with a coarse sand was used to cast all the specimens.

2.2 Test Setup and Instrumentation

Diagonally loaded specimens were tested in a Baldwin universal testing machine. For other tests, racking loads were applied at the centreline of the top beam through a hydraulic ram pinned at both ends to allow rotation as the the specimen deformed. This setup is shown in Figure 1. In diagonal tests, steel shoes were inserted between the universal testing machine heads and the specimens loaded corners. High contact forces were avoided by positioning masonite pads between the steel shoes and the test units. In racking tests, the point of the load application was reinforced by a built-up epoxy surround to prevent it from crushing prematurely. A similar technique was applied successfully by Dukuze and Dawe (1996) on three-storey, three-bay RC infilled frames. A load cell was placed between the frame and the ram to monitor the applied lateral force. At each 4.5-kN load increment, specimens were inspected for cracks which were thereafter reported on templates. Tests were stopped when specimens were excessively damaged or the recording instruments ceased to function. The instrumentation and loading procedure were similar in diagonal and racking tests. All specimens were instrumented so that compressive diagonal deformations along with the acting load were continuously recorded. In-plane lateral drift at the level of the top beam was recorded for frames subjected to racking load.

3 Test Results and Discussion

A total of fifteen square RC infilled frames were built and tested. While only four specimens including S1PD, S2PD, S5PD and S1BD were subjected to in-plane racking forces, eleven units comprising S1P, S2P, S5P and S1B series were diagonally tested. Results related to these tests are reported herein and discussed with respect to load vs displacement curves, in-plane resistance and stiffness, and failure modes. Table 2 summarizes the results of both test setups. While results from racking load tests refer to a single specimen for each category, a range of mechanical properties is reported for diagonally loaded units to reflect the resulting scatter within each series of similar specimens.

3.1 Load vs Displacement Curves and In-plane Resistance

Using recorded data, the horizontal component of applied force was plotted against the compressive diagonal displacement. These curves are summarized in Figures 2, 3 and 4. The in-plane behaviour of infilled frames reflected in these curves could be subdivided into a pre-cracking, a post-cracking, and a post-peak phase.

Characterized by a linear response, the pre-cracking phase extended up to the occurrence of a diagonal crack in the masonry infill followed by a noticeable drop in loading. The horizontal load at which the diagonal crack occurred in masonry walls, referred to as H_c, depended on the beam-to-column relative stiffness of the specimens. Stiffer than other test units, specimens with strong columns yielded high values of H_c. Independent of the loading mode, H_c reported from racking tests were in the range of diagonal test results as shown in Table 2.

In the post-cracking phase, cracks were observed to be approximately parallel to the infill compressive diagonal direction as they propagated towards loaded corners. Subsequently, the crushing of mortar joints and loaded corners induced a nonlinear behaviour of the composite system. As the load increased, the diagonal crack at the center of the masonry panel widened and propagated towards the ends of the compression diagonal. During this phase, frequent load drops due to slip along mortar bed joints were observed. As the specimens got closer to their respective ultimate resistances, existing cracks extended as new ones initiated.

After the maximum load, the post peak response depended on the interlocking effect between the panel and the deformed frame. At this stage, brick units of the degraded panel underwent substantial slip and rotation in order to fit the deformed shape of the surrounding RC frame. This phenomenon was accompanied by stress redistribution within the masonry panel due to the high level of frame normal contact forces and mortar joint openings. With respect to load vs displacement curves, this phase constituted the most distinctive characteristic of both types of loading. When specimens were tested diagonally, an abrupt drop in load followed the attainment of the maximum. Racking load application, on the other hand, resulted in gradual strength degradation as illustrated in Figures 2 and 4 for S1PD and S2PD, respectively. Although the racking load tests indicated slightly stronger infilled frames, the in-plane resistances referred to as H_u compared well with the strengths obtained from diagonal tests as shown in Table 2.

3.2 In-plane Stiffness and Failure Modes

Three different rigidities K_i, K_c and K_u were defined as the initial tangent stiffness, secant stiffness at the first major crack and the secant modulus at ultimate, respectively. While K_c reflects the effective stiffness of an infilled frame, K_u represents the residual stiffness at an extensive specimen deterioration. Both testing modes revealed that masonry infills markedly enhance the in-plane stiffness of the system. Since specimens tested in racking mode were provided with a very strong base beam, the in-plane responses were altered in comparison with those of diagonally loaded walls. This led to high initial stiffness which was reflected in load vs displacement curves. Initial stiffness values of K_i are shown in Table 2. Although the specimens were extensively damaged at ultimate, they were still stiffer than the corresponding open frames.

With minor differences, both test setups yielded similar failure patterns. Failure modes were mainly characterized by substantial cracking of infills and by localized crushing of frame members. Most cracking took place after the occurrence of first diagonal cracks. Subsequently, cracks developed in frame members whose beam-to-column joints opened up at loaded corners. As loading proceeded during the post-ultimate response, RC frame columns sustained extensive damage in a typical pattern associated with a combination of bending and shear failure. After marked panel deterioration and frame distortion further loading led to initiation of plastic hinges in frame members. While both test setups yielded similar failure patterns, specimens subjected to racking loads were more prone to hinge formation at the mid-height of windward columns especially for specimens with light members as shown in Figure 5. This damage pattern referred to as knee-brace failure mode is consistent with observations reported by Fiorato et al. (1970). The similarity of the behaviour of diagonally loaded and racking load specimens was more readily evident for specimens with higher relative beam-to-column stiffness as illustrated in Figure 6.

3.3 Open Frames

As shown in Figure 7, open frames responded linearly before exhibiting a nonlinear behaviour in the vicinity of ultimate strength. Beyond that point, specimens behaved typically as elasto-plastic structural systems irrespective of the loading type. S1B1, S1B2 and S1B3 were diagonally loaded while S1BD was subjected to a racking test. Although both test setups resulted in comparable initial stiffnesses, racking load tests yielded high ultimate resistances as shown in Table 2 due to the stiffening affect of the strong base frame.

The observed damage due to extensive deformation of open frames was concentrated at the corners. The loaded joints crushed while the unloaded corners closed up. Damage which was initiated during the nonlinear phase extended substantially during the post-peak response. Because of the extensive deterioration of the corners, a frame mechanism resulted from the formation of hinges in the corners.

4 Conclusions

The general response of specimens tested diagonally was compared to the performance of those subjected to a lateral in-plane racking force. Both testing procedures confirmed the enhancement effect of masonry infill panels with respect to strength and in-plane stiffness of open frames. Whereas load vs displacement curves for both types of loading were similar in the pre- and post-cracking stages, a gradual degradation was more evident in racking test than in diagonal loading. Although the racking load results indicated high initial stiffness, both modes of testing produced comparable general behaviour with respect to the load vs displacement curves up to the ultimate, and the failure modes. Within the limit of this study, diagonal setup is more flexible and economical since it can be easily accommodated by test equipment available in most structural laboratories. Without the interference of strong base beams provided to specimens under racking load, diagonal tests are suitable in investigating infilled frames with members of different sizes provided the specimen scale is appropriate.

5 Acknowledgements

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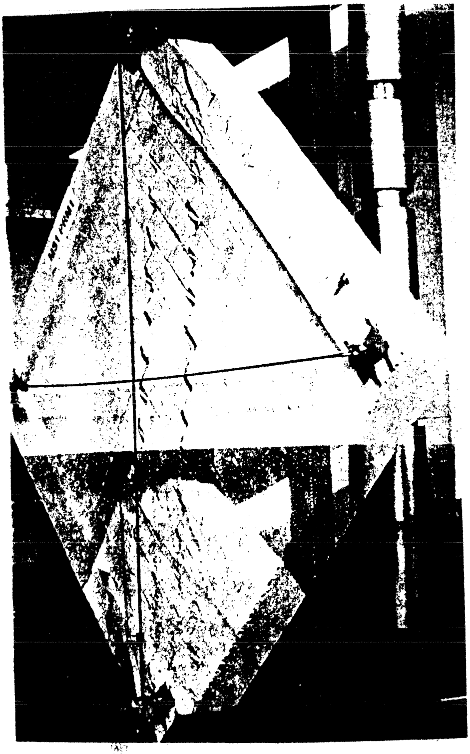
Table 1: Specimen Member Dimensions

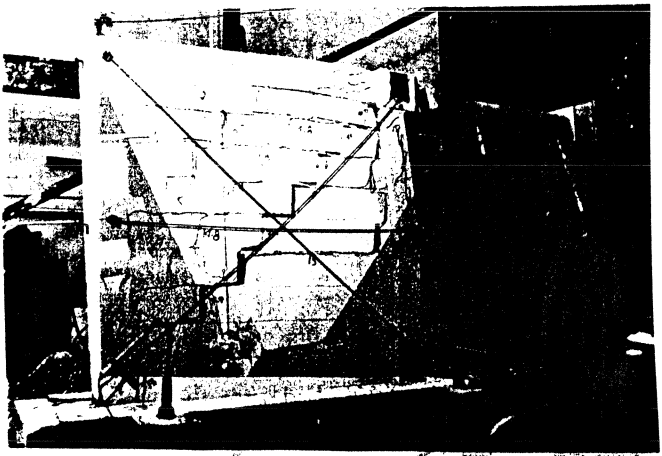
Specimen	Beam mm x mm	Column mm x mm	I_b/I_c	Masonry Wall	Load Application	Number of Specimens
S1PD	100 x 100	100 x 100	1	Yes	Racking	1
S2PD	100 x 100	100 x 170	0.2	Yes	Racking	1
S5PD	100 x 170	100 x 100	5	Yes	Racking	1
S1BD	100 x 100	100 x 100	1	No	Racking	1
S1P	100 x 100	100 x 100	1	Yes	Diagonal	3
S2P	100 x 100	100 x 170	0.2	Yes	Diagonal	2
S5P	100 x 170	100 x 100	5	Yes	Diagonal	3
S1B	100 x 100	100 x 100	1	No	Diagonal	3

Table 2: Summary of Experimental Results

Specimen	H_c kN	H_u kN	K_i kN/mm	K_c kN/mm	K_u kN/mm
S1PD	31.8	69.5	88.57	87.6	15.5
S2PD	51.6	108.3	92.73	85	19.1
S5PD	38.1	117.5	34	34	2.95
S1BD	NA	20.1	2.07	NA	0.91
S1P	28–37	58–84	25–84	15–80	2.4–19
S2P	59–79	93–100	89–140	44–140	22–25
S5P	18–42	65–102	46–71	43–48	3–11
S1B	NA	11–15	1.1–2.8	NA	0.9–1.1



(a) Diagonal Test



(b) Racking Test

Figure 1: Test Setup and Instrumentation for Racking and Diagonal Test

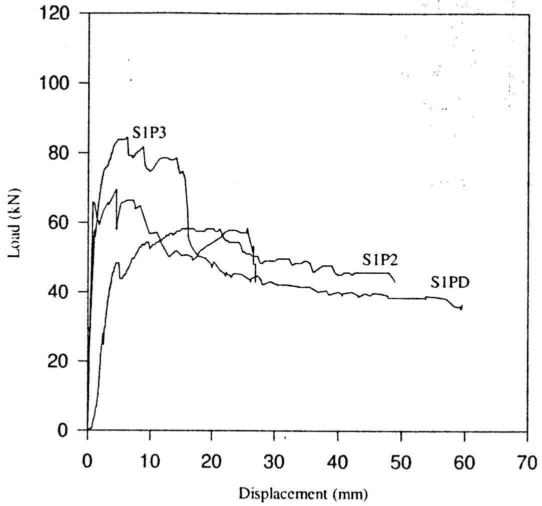


Figure 2: Load vs Diagonal Displacement for S1P and S1PD Specimens.

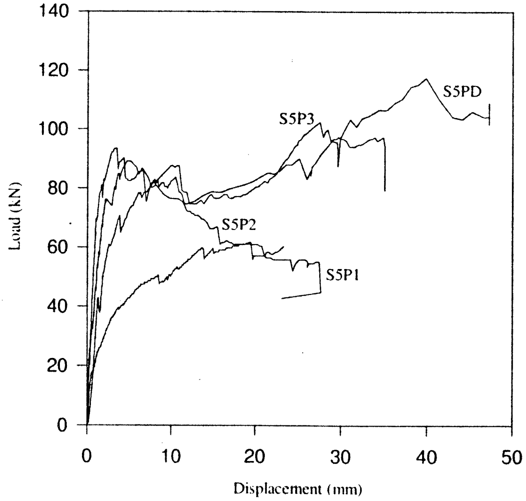


Figure 3: Load vs Diagonal Displacement Curves for S5P-Series and S5PD Specimen.

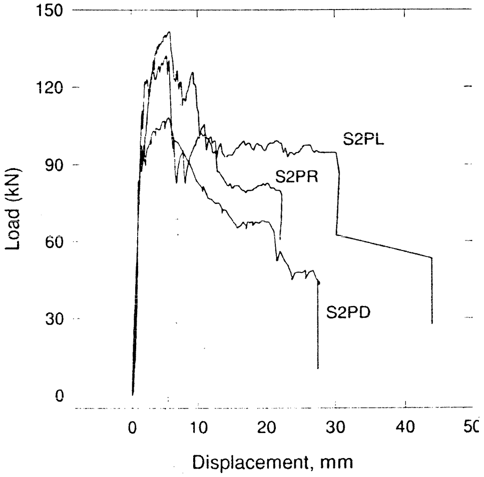
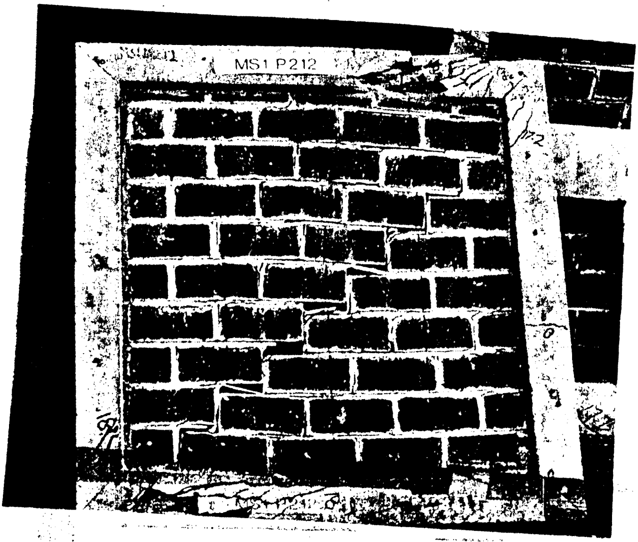
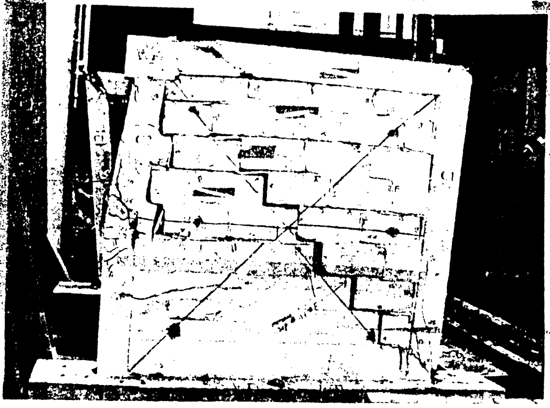


Figure 4: Load vs Diagonal Displacement for S2P-Series and S2PD Specimen.

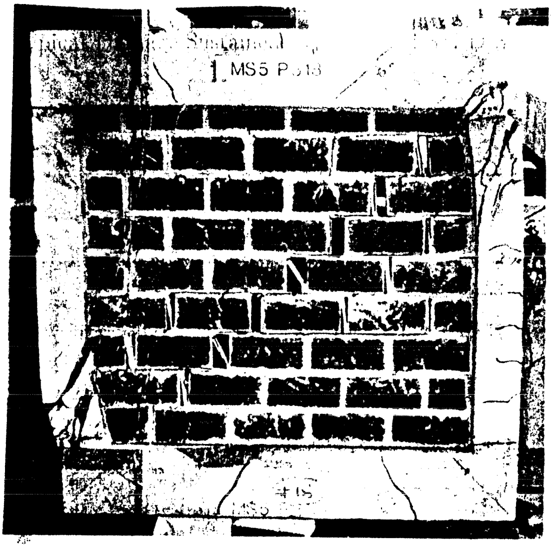


(a) Diagonal Test

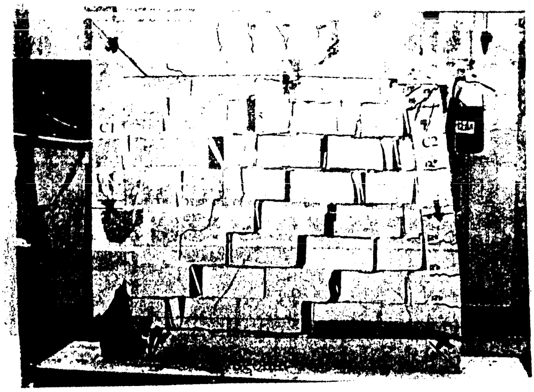


(b) Racking Test

Figure 5: Typical Damage Sustained by S1P2 and S1PD Specimens.



(a) Diagonal Test



(b) Racking Test

Figure 6: Typical Damage Sustained by S5P3 ad S5PD Specimens

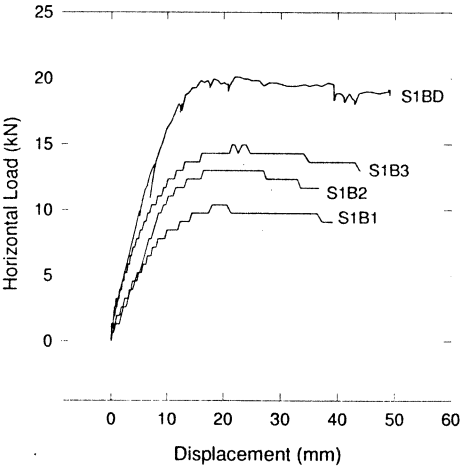


Figure 7: Load vs Diagonal Deformation of S1B and S1BD Open Specimens.