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Hybrid Reinforced Concrete Frame Building with Pumice Brick Masonry Infill under Static Lateral Loading

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ABSTRACT

The purpose of this study is to investigate the behaviour of hybrid reinforced concrete frame with pumice brick masonry infill under static lateral loading. The term hybrid herein is referred to the frame composed of precast block masonry unit and cast in-place reinforced concrete beams. Parameters considered in this study were frame opening representing doors and windows commonly used in the wall system. Six types of frame namely FS, FB, FDE, FDC, FWE and FWC designation for solid frame, bare frame, frame with door opening at edge, frame with door opening at centre, frame with window opening at edge and frame with window opening at centre respectively were considered. Test results indicated that the FS has a maximum lateral strength greater than that of FB. The lateral strength of FS was about 3.68 of FB. The frames with various openings have lateral strength nearly 2.3 of lateral strength of the bare frame, FB. Ductility factor of the frames varied from 2.4 to 4.92. The residual strength of the frame with openings were varies between 2.33 and 3.35 of the bare frame. The stiffness of the infilled frames with opening were varied from 3.56 to 3.67 of the bare frame. The presence of openings in the infilled frame did not affect the frame stiffness considerably.

Keywords: *Infilled frame, openings, stiffness, lateral strength, hybrid*

1. INTRODUCTION

Reinforced concrete (RC) frame buildings with masonry infill wall represent a common type of construction for residential and commercial buildings in areas with high seismic risk. The RC frames, consisted of column and beam, typically were considered as structural element in design process while the infill walls were treated as non-structural component [1]. A number of researchers have studied the infill wall in the RC frame and results of their investigations showed that the infill wall enhances strength, stiffness and ductility of the RC frame [2, 3]. The presence of openings in the infill wall as representation of window and door in the wall system were also studied by many investigators. Their results concluded that the opening in the infilled frame play significant effect on the performance of the frame [4, 5]. Damage to buildings caused by the earthquake has paid attention of researchers to study seismic strengthening technique of infilled RC frame. Infill wall commonly made of masonry brick with strength lower than the frame strength in the frame system, thus this component usually often found damages earlier in the post-earthquake. Retrofit this component or replaced by new panel with special strengthening were the focus of the researcher to improve performance of the infilled frame [6, 7]. Various types of material infill also studied in terms of their contribution to the strength of infilled frame. Comparison of material characteristic such as autoclaved aerated concrete (AAC) blocks and infill wall using clay bricks material was also obtained [3]. In addition to experimental works on infilled frames, many analytical studies were also conducted [8, 9, 10]. Two kinds of loading application were used in the experimental study conducted by Xu and Yang [11]. The useful result obtained from this study was the load carrying capacities of infilled frame due to cyclic loading was approximately equal to that under monotonic loading. However, ductility under monotonic loading was approximately 10% greater than that of corresponding value under cyclic loading. These results were adopted in this study in terms of interpretation of results obtained during this study.

Low-cost housing programme commonly introduced in developing countries would be realized when locally available materials are utilized extensively for housing construction. The implementation of precast concrete component would save in time the building construction process hence the construction period at site could be shortened. This as a result of no longer needed the formwork and no need to wait until placement and curing of the concrete element are reached. Generally, the manufacture of concrete column in the practical work was carried out by the cast in place of the concrete. In this way, quality of formworks and a strict control of works are required to guarantee that the concrete uniformity and casting columns in line position are met. Poor formworks and supervision of such work can lead to skewed column and poor column quality. Thus, by using precast columns would guarantee the qualities of the columns as designed are achievable, relatively clean, precise, and does not require much labour. However, a large investment in equipment is required. Considering the advantages and disadvantages of this system then utilization of locally available material of pumice lightweight concrete masonry unit as precast column and pumice concrete bricks masonry unit as infill wall of the frame system are introduced.

Figure 1. Frame construction of precast block-masonry unit column

The columns are made using a set of concrete block masonry unit reinforced with longitudinal steel reinforcement installed continuously with shear links provided at 150 mm spaces. The blocks masonry unit are bonded to each other using mortar joint. Detail of this columns type is presented in Figure 1.

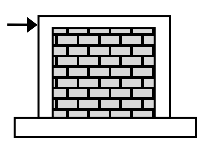
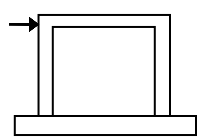
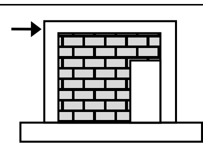
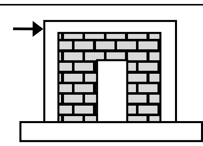
The use of precast column and cast in place concrete beam reinforced with steel as the frame component is referred to hybrid reinforced concrete frame. The precast masonry unit columns are prefabricated in-house so that the columns quality can easily be maintained. This system would have economical advantages concerning the construction of low rise residential building in developing countries especially in rural areas of Indonesia. Cost savings inherent in this construction system is in terms of labour cost and time reduction as the works would be finished quicker than that of the traditional system. Finally, the application of this column type as part of the hybrid frame system would accelerate the house construction process. Due to lack of knowledge concerning behaviour of such type of the infilled frame therefore this study aims are to obtain the behaviour and lateral strength of the hybrid frame under monotonic lateral loading.

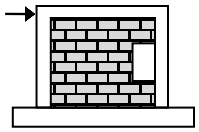
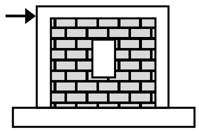
2. EXPERIMENTAL PROGRAM

2.1 Test Specimens

In the conducted experimental study, six specimens were constructed and tested at Structure and Material Laboratory of Mataram University. The test specimen designations and their properties are summarized in Table 1.

Table 1: Properties of Test Specimens

Specimen ID	Configurations	Openings	
		Location	Opening to Infill Wall Ratio
FS		-	0
FB		-	1
FDE		Edge	0.36
FDC		Centre	0.36

Specimen ID	Configurations	Openings	
		Location	Opening to Infill Wall Ratio
FWE		Edge	0.18
FWC		Centre	0.18

The specimens considered in this study were consisted of about one-third scale, one-bay, and single-story hybrid RC frames. The test hybrid frames represent the most common frame having deficiencies in practice such as strong beam-weak column connections, insufficient confinement, low concrete strength and poor workmanship. Shear links of 6 mm plain bar were provided. They were placed after installing block masonry unit column with produce a spacing of 150 mm. The beam column joints were not confined. The gross columns dimension was 150 x 150 mm and the beams were 120 x 150 mm. Four 8 mm diameter plain bars of 250 MPa yield strength were used as longitudinal bars in both column and the beam. The dimensions and reinforcement details of the test frames are illustrated in Fig. 2.

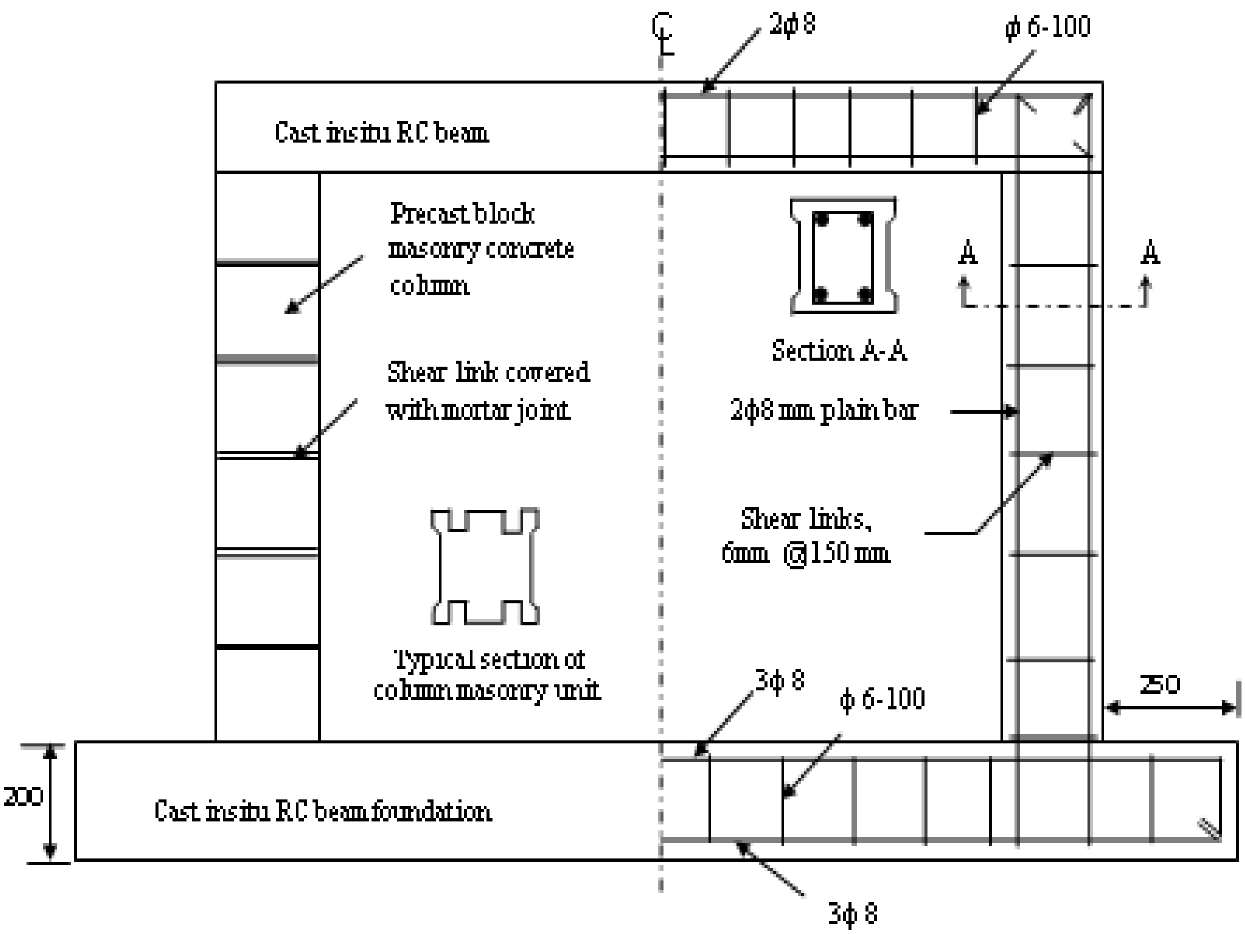


Figure 2. Hybrid RC Frame Details

All frames were infilled with pumice bricks with size of 45 x 100 x 210 mm, that made of mixture of cement, sand and pumice with composition by volume of 1, 2 and 4 respectively. The bricks were laid such that their smallest thickness was vertically oriented. The thickness of mortar joint was about 10 to 15 mm. The infill wall was constructed centrically on the axis of the frame. The columns of the frames were constructed from pumice masonry lightweight concrete block connected with longitudinal reinforcement and steel stirrup tied at 150 mm and finally mortar was plastered as connection and reinforcement cover. Cast in-place concrete for the beam was got using the plywood moulds with a size of 120×150×1150 mm. For the foundation beam, it was made of the plywood moulds of 150×200×1350 mm.

2.2 Materials

The concrete strength of the test frame was approximately 17 MPa for both precast column and cast in situ beams. The lightweight concrete strength of precast column was achieved by maintaining concrete mixture, for 1m^3 concrete, with proportion of cement, sand and pumice at 507.50, 467.23, 382.28 kg respectively with water to cement ratio of 0.4. While the beam strength, of normal concrete, was obtained using mix proportion of cement, sand and gravel of 380, 739 and 1108 kg respectively for 1 m^3 concrete mixture. Water to cement ratio used was 0.45. The brick masonry infill walls were produced using mix proportion by volume of cement, sand and pumice of 1, 3 and 5 respectively. This mixture produces strength of bricks infill approximately 5.17 MPa on the day of testing. Mortar was made by volume proportion of cement and sand of 1 and 2 respectively to produce design strength of 20 MPa. Longitudinal and shear reinforcements used in this study were mild steel of 250 MPa yield strength. The concrete compressive strength and the unit weight of the concrete on the day of testing frame are listed in Table 2.

Table 2: Material Properties

Element types	No	Designation	Unit weight (kg/m^3)	Categories	Compressive strength f'_c, (MPa)	Average (MPa)
Block concrete masonry unit for column	1	C1	1,655	Lightweight concrete	20.37	17.72
	2	C2	1,607		22.35	
	3	C3	1,645		16.13	
	4	C4	1,658		16.69	
	5	C5	1,664		19.24	
	6	C6	1,616		16.41	
	7	C7	1,608		14.15	
	8	C8	1,612		16.41	
Foundation	1	F1	2,473	Normal concrete	22.07	23.48
	2	F2	2,369		24.90	
Beam	1	B1	2,447	Normal concrete	16.69	18.25
	2	B2	2,504		19.81	
Pumice Brick masonry infill	1	BR1	693	Lightweight concrete	4.76	5.17
	2	BR2	680		4.39	
	1	BR3	712		6.71	
	2	BR4	688		4.76	
	1	BR5	707		5.24	

Instrumentation and Test Procedure

Figure 3 shows details of test setup, loading system, and instrumentation used in this test. The Frame foundation was anchored to the laboratory's rigid floor by high-strength steel bolts. A steel frame was constructed in line with test specimen to put head of loading. Specimens were tested under static lateral loading applied concentrically to the beam section at the top of the frame. The lateral load was created by a hydraulic jack of ENERPAC with 100 kN capacities. A load cell was connected between the hydraulic jack and the test frame. A dial gauge for measuring lateral deflection was installed in the top of the test frame. Displacement control was applied. The tests were carried out by 1 mm lateral displacement incremental in the top frame. During the test, displacements and the lateral loads applied to top frame were noted. At each load increment, cracks were marked on the specimens and the mechanism of failure was observed during testing.

Figure 3: Set-up Testing

Prior to the frames tests conducted, the cylinder specimen of 150 diameter and 300 mm height is prepared to obtain the compressive strength of precast columns. A "CONTROL" compression machine of 2000 kN capacity was used to obtain compressive strength of the cylinder specimen. Procedure used was refers to the ASTM standard test. While the compressive strength of masonry infill wall was obtained using similar machine test with procedure refers to BS EN 1052-1:1999 [12].

3. RESULTS AND DISCUSSIONS

3.1 Behaviour of Test Specimens

The behaviour of infilled frames tested under static lateral load is studied by performed diagram relationship between lateral load and displacement as presented typically for hybrid frame with fully infill wall in Figure 4. As mentioned previously deflection control was adopted in this test, thus deflection was set initially at 1 mm with increment of 1 mm. For this typical frame, the 1 mm lateral deflection was achieved by load given of 13.49 kN as can be seen in Figure 4. At this load level, observation on test specimens showed no cracks occur on the surface of the frame. Cracks start to occur at lateral deflection of 3 mm corresponding with load acting of 20.25 kN. The first cracks was noticed occur at column element where exactly in the joints between the block-masonry units. This was expected as the block masonry unit column was connected using mortar where these materials have different properties. When simplified line was drawn trough the load-deflection coordinates then two linier lines was obtained. These lines intersect between axis point 2 and 3 mm which produce the slope angle of α as can be seen clearly in Figure 4. The change direction of the lines tells that cracks have begun to occur. This statement is consistent with the test specimen observation, where cracks taking place at deflection of 3 mm as previously mentioned.

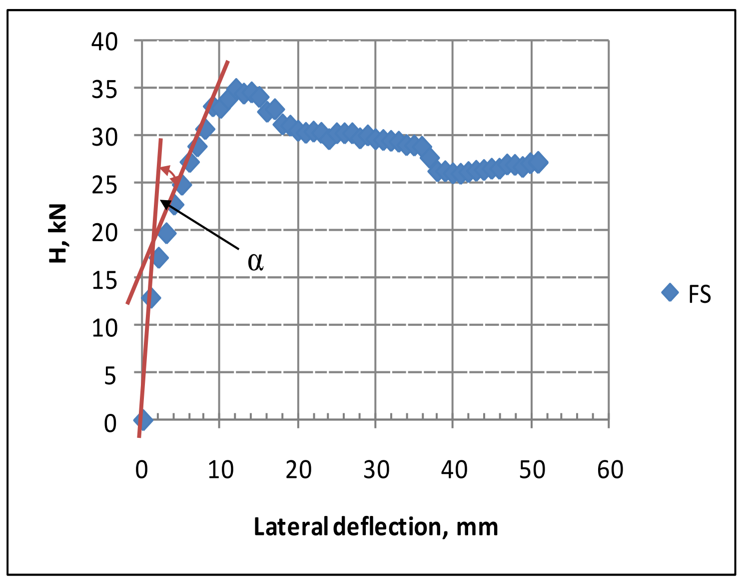


Figure 4: Fully Infilled Frame Behaviour under Lateral Loading

With increasing deflection, the load increase gradually and the cracks began to spread from column to the infill walls of the frame. Major cracks were observed at deflection of about 9 mm. After the major cracks occurred on the frame, a small increment on the lateral load was noticed and reach maximum value of 35 kN which correspond to deflection of 13 mm, the loads then gradually decreased and constant for a while until deflection reach 38 mm as can be seen in Figure 4. The loading then drop and the test was stopped after maximum deflection of 50 mm was reached. At this step, physically the infill wall began to crush and separate from the columns, the frame lost its lateral load carrying capacity and thus failed. Figure 5 shows test results of fully infilled frame tested.

Figure 5. Failure pattern on hybrid frame with fully infill wall

Overall specimens tested behave similar with those explained above with variation in lateral load carrying capacity and deflection relationship as can be seen in Figure 6. It is clear from the figure that the bare frame, FB, behaves much different with others in terms of their load carrying capacity.

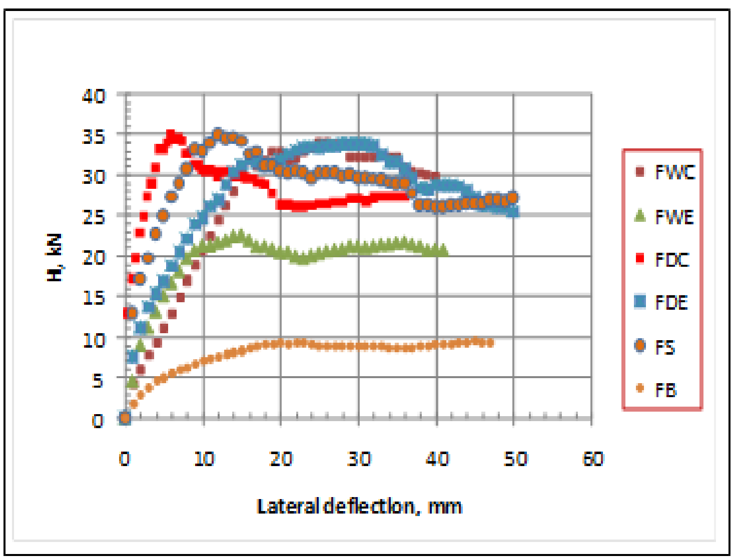


Figure 6. Various Lateral Load-Deflection

It has also been noticed from the physical test result that all the frames had typical cracks propagation in the form of diagonally spread in the infill wall. The cracks approximately made a 45-degree angle which begun from the top compression corner to the base of the frame with were joined by horizontal sliding cracks developed along the bed joint near the mid-height of the infill wall. This can be seen in Figure 5, 7, 8(a) and 8(b) for FS, FDC, FWC, and FDE respectively. However, FWE had cracks propagate vertically then joined with sliding cracks horizontally developed between the bed joint near the top of the opening as can be seen in Figure 8(c).

Figure 7: Failure pattern of FDC Hybrid Frame under Lateral Loading

a. FWC

b. FDE

c. FWE

Figure 8: Test specimens after Failure of Hybrid Frame under lateral Loading

3.2 Lateral Strength Variation of the Frames

Shear strength of the infilled frame herein refers to the ability of the base frame to resist lateral load acting on the frame commonly used the term lateral strength or base shear capacity. Thus, lateral load carrying capacities of the frames tested were summarized in Table 3. When the bare frame is made as a frame reference and all the frames are normalized to that frame thus results are presented in column (5) of Table 3.

Table 3: Various Shear Strength Capacities of Infilled Frames

Specimen ID	Description	Opening Ratio	H_{max} (kN)	*v*
(1)	(2)	(3)	(4)	(5)
FB	Bare Frame	~	9.48	1
FS	Solid Frame	0.00	34.93	3.69
FWC	Frame in-filled partially with opening at the centre of wall representing window	0.18	33.91	3.58
FDC	Frame in-filled partially with opening at the centre of wall representing door	0.36	30.35	3.20
FWE	Frame in-filled partially with opening at the edge of wall representing window	0.18	22.56	2.38
FDE	Frame in-filled partially with opening at the edge of wall representing door	0.36	33.82	3.57

It can be seen from the table that lateral strength of all infilled frame were considerably greater than that of the bare frame. The ratio of the lateral strength of the infilled frame to the lateral strength of the bare frame varied from 2.38 to 3.69. The maximum lateral strength of the solid frame, FS, was 3.69 of the bare frame or 268% greater than that of the bare frame lateral strength, FB. The infilled frame having opening ratio of 0.36 was approximately similar with infilled frame having opening ratio of 0.18 (FWC, FDC, FDE). However, FWE having opening ratio of 0.18 was significantly different. It was noticed from the observation of the test specimen that the column frame of FWE failure earlier than expected which probably due to poor workmanship during the block masonry specimen constructed. This can be argued by the compressive strength of 14 MPa obtained from the cylinder specimen test as presented in Table 2. The cracks propagation of this frame clearly can be seen in Figure 8(c) above. Thus, in general the presence of opening with ratio less than 40% have no significant effect in terms of lateral strength. These results are consistent with the analysis results given by Nwofor and Chinwah [13].

3.3 Drift ratio, cracks condition and residual strength

Drift ratio is a term commonly used in terms of lateral deformation in the building frame due to loading and used to control the extent of structural and non-structural damage in a building [1]. It is defined as the ratio between the lateral deflection and height of the frame. Thus, lateral load-deflection curves as presented previously can be modified in the form of load-drift ratio relationship as typically presented in Figure 9. The figure can be used to classify the cracks in the frame in terms of their drift ratio [4]. For this typical graph, Figure 9, it has been observed that major cracks occur at the branch of line 1 and line 2 corresponding to γ_y in which steel reinforcement of the column frame started to yield. The ultimate cracks were specified by intersection of line 3 and peak of the curve as shown in Figure 9 which namely γ_u.,

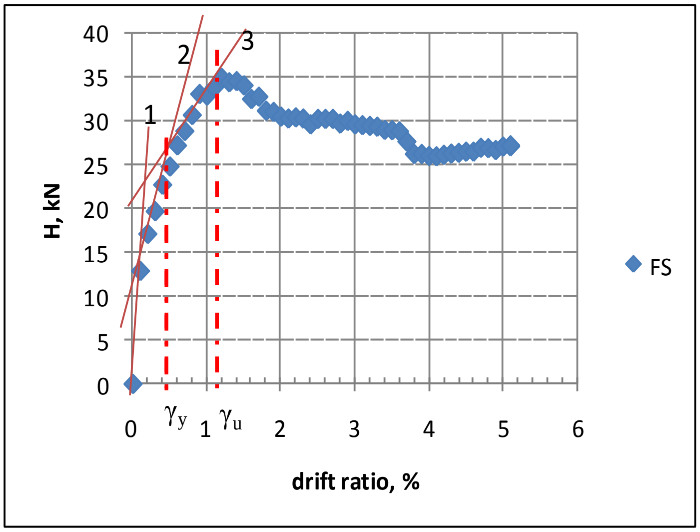


Figure 9: Lateral load vs Drift Ratio

From the definition above, Table 4 summarized the drift ratio in which major crack and ultimate cracks occur on the frame for all specimens tested.

Table 4: Drift ratio at Serviceability and Ultimate Limit State

Specimens ID	Opening ratio	γ_y (%)	γ_u (%)	H_{ult} (kN)	β_{res}
(1)	(2)	(3)	(4)	(5)	(6)
FB	~	1.40	4.50	9.43	1.00
FS	0.00	0.45	1.30	34.93	2.93
FWC	0.18	1.00	2.60	33.91	3.35
FDC	0.36	1.00	2.90	30.35	2.96
FWE	0.18	0.80	1.70	22.56	2.33
FDE	0.36	1.20	3.20	33.82	3.17

Table 4 shows that in all specimens the major cracks, γ_y, occur at a drift value between 0.45% and 1.20% which can be regarded as serviceability limit state for this type of structure. In general, Infilled frames have yield drift ratio smaller than the drift of bare of 1.4%. Similarly, the ultimate drift ratio of all infilled frames varies between 1.30% and 3.20% in which smaller than that of the bare frame of 4.50%.

Furthermore, when residual strength was measured at maximum drift ratio of 4% then the residual strength of all frames tested are obtained and presented in column (5) of Table 4 above. Ratios of the residual strength of the frames to the residual strength of the bare frame, β_{res}, are presented in column (6) of table 4. It can be seen from the table that the normalized residual strength of the frame with infill wall varies from 2.33 to 3.17 of the bare frame and did not seem to be relies on infill wall opening ratio.

Ductility of Frame

In addition to drift ratio, it is commonly used parameter ductility ratio to measure the performance of structure beyond elastic range. Experimentally, it can be obtained using the load-deflection curve presented previously in Figure 6. The ductility factor, μ, is defined as the ratio between the ultimate deflection and the yield deflection which is produced by obtaining the ultimate load reduction to 85% on the curve [4]. This would correspond with two intersection points of Δ_y and Δ_u which is corresponding to yield deflection and ultimate deflection respectively. For more convenient, Figure 10 illustrates procedure to obtain those values by drawing a straight line of 0.85 H level, intersecting at two points, one at the ascending (Δ_y) and the other at the descending branch (Δ_u).

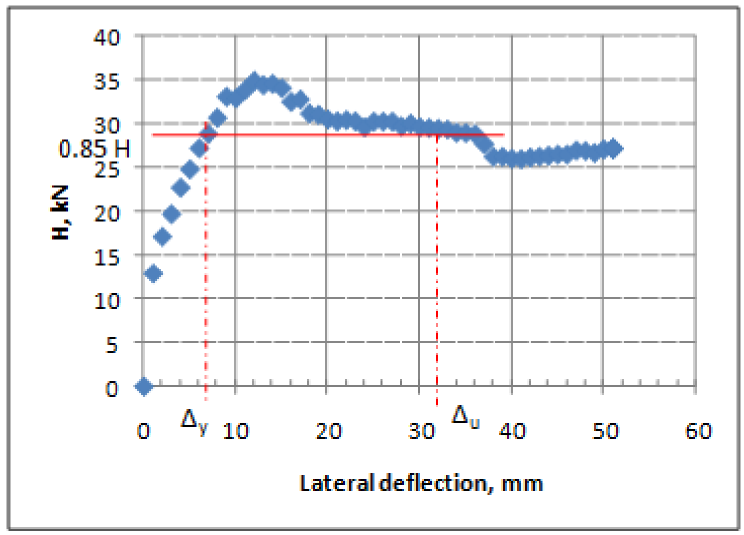


Figure 10: Definition of Frame Ductility [4]

Table 5 summarizes the results obtained for the ductility factor, μ, for all frames specimen. The ductility factor varies from 2.4 to 4.92. The ductility factor for the frame with fully infill and the bare frame was 4.92 and 2.95 respectively. In general, the ductility factor of the frames having door opening have slightly higher than that of the frames having window opening.

Table 5: Ductility Factor of Frames

Specimens ID	Opening ratio	Δ_1, mm	Δ_2, mm	μ
(1)	(2)	(3)	(4)	(5)
FB	~	12.20	36.00	2.95
FS	0.00	6.50	32.00	4.92
FWC	0.18	15.00	36.00	2.40

FDC	0.36	10.00	44.00	4.40
FWE	0.18	7.50	23.00	3.07
FDE	0.36	12.50	39.00	3.12

3.5 Stiffness of Frame

In general, stiffness was ratio between force acting and deformation. Figure 11 used to obtain initial stiffness of the frames. It was obtained from the figure an intersection point in the lateral load-deflection curve, which produces yield deflection representing major cracks on the frame and corresponding to yield load (H_y). Thus, the initial stiffness, K_o, is defined as ratio of the yield load and the yield deflection [4].

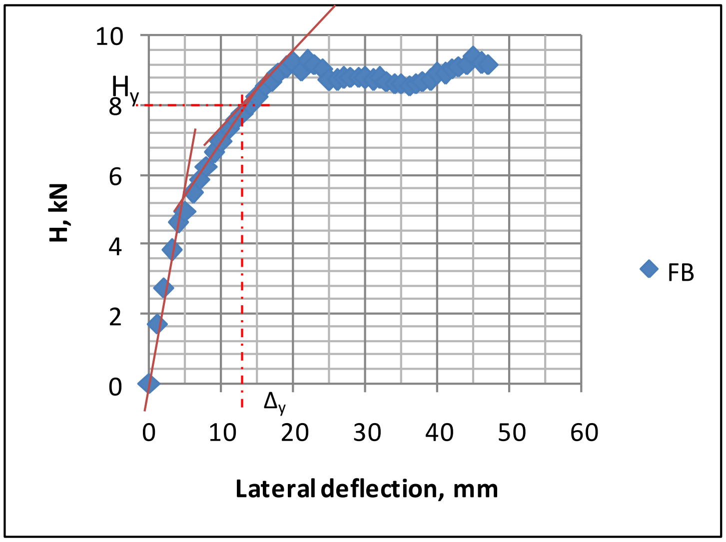


Figure 11: Definition of Frame Stiffness [4]

The results of investigations for all frames are presented in Table 7. When the frames stiffness values are normalized to bare frame stiffness denoted by *k*, then the normalized stiffness the frames are given in column (5) of Table 7.

Table 6: Stiffness of Frames

Specimen ID	Opening ratio	H_y (kN)	Δ_y (mm)	K_o (kN/mm)	*k*
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
FB	~	7.20	11.00	0.65	1.00
FS	0.00	29.00	7.00	4.14	6.33
FWC	0.18	24.00	10.00	2.40	3.67
FDC	0.36	25.00	10.00	2.50	3.82
FWE	0.18	19.00	8.00	2.38	3.63
FDE	0.36	28.00	12.00	2.33	3.56

Table 7 clearly shows that the existence of infill wall increases frame rigidity significantly. The observations indicated that ratio stiffness of the infilled frames to bare frame were varies between 3.56 and 6.33. The solid infilled frame, FS, has the highest ratio stiffness values of 6.33. The ratio stiffness of infilled frames with opening have values about half of the solid frame. Thus the opening ratio of infill wall did not significantly affect the value of stiffness of the infilled frames with opening.

CONCLUSIONS

Based on the results obtained in this study the following conclusion can be drawn:

a. Lateral behaviour of the infilled frame slightly similar to the behaviour of beams under flexural loading.
b. The frame with fully infill wall has lateral strength greater than that of the frame with empty wall. The former has lateral strength of 34.93 kN and the latter of 9.48 kN. The frames with various openings have lateral strength nearly 2.3 of the lateral strength of the bare frame.
c. Drift ratio of the frames at serviceability limit state varies from 0.45% to 1.4% and at the ultimate limit state were varied between 1.3% and 4.50%. While the ductility factor of the frame varied from 2.4 to 4.92.
d. The residual strength of the frame with openings were varies between 2.33 and 3.35 of the residual strength of the bare frame.
e. Stiffness of the infilled frames with openings have variation values from 3.56 to 3.67 of the bare frame stiffness. The presence of openings in the infilled frame did not affect the stiffness significantly of the frame.

Finally, the possibility to use blocks masonry unit as component of precast columns in the frame with infill wall are widely open especially for the low-cost housing program in developing countries.

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