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Experimental evaluation of damage state and failure propagation of infilled frames under the opening effect

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Abtract: In this study, four frame specimens were tested: two with concentric window and door openings in the infills, and two with eccentric window and door openings. The serviceability limit of the infilled state was determined by evaluating the structural behaviour of infilled reinforced concrete frames with openings. The results indicate that frames with centrally located openings exhibit a reduction in lateral load capacity. The damage characteristics are influenced more by the location of the opening than by its percentage. When the opening is positioned closer to the edge of the masonry panel, the structural performance improves. Initial cracking occurs at a lateral drift of 0.2%, while crushing of the masonry panel occurs at approximately 2%. In frames with centrally located openings, the segment near the loaded column is more prone to damage, whereas the segment farther from the loaded column shows increased vulnerability.

Keywords: Concentric; Eccentric; Damage characteristic; Lateral drift

1. Introduction

The interaction of infill wall with structural frame system can be seen obviously during seismic action, potentially leading to unexpected and undesired failure mechanisms at high drift level. The behaviour of infilled frame is difficult to predict the different material composition of concrete, steel, brick units and mortar [1]. Under lateral loading, the behaviour of the infilled wall structure is evaluated by experimentally and analytically based on the local damage level, which is correlated with the global engineering parameter of inter-story drift ratio [2]. Due to the complexity of factors influencing the interaction between masonry infills and reinforced concrete frames, it is imperative to systematically observe and analyse various parameters to accurately assess the structural performance [3][4][5][6][7]. These factors include (i) the stiffness of the reinforced concrete frame, (ii) the compressive strength of the masonry, (iii) the shear bond strength of the masonry, (iv) the aspect ratio of the panel, (v) the size and location of openings within the infill and so on. Given the interplay of these variables, thorough evaluation is

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required to ensure an accurate understanding of the structure's behaviour under different loading conditions.

During an earthquake, infill masonry walls may be subjected to two types of loading, depending on their orientation relative to the principal direction of seismic excitation: in-plane loads and face loads that can result in out-of-plane collapse [1][2]. Commonly observed in-plane failure modes include sliding along mortar bed joints, diagonal cracking through masonry units, step cracking or sliding along mortar joints, and toe crushing. These typical failure modes are illustrated in Figure 1.

Due to the limited research on infill panels in Myanmar, the current building code lacks specific provisions, and there are no available guidelines for their design. Additionally, assessing the damage to brick-infilled reinforced concrete framed buildings caused by earthquakes remains challenging when using conventional analytical methods. Therefore, experimental investigations are necessary to determine the material properties of locally sourced bricks and to evaluate the performance of infill masonry walls. Such investigations can also provide insights into the propagation and modes of failure within these structures.

This paper aims to limit the performance level of structure and to develop a comprehensive classification system for the failure modes of infilled frames considering the window and door opening effect. This study proposes various structural damage limits based on the lateral drift ratio. Three distinct damage states associated with window and door openings are identified. The investigation also focuses on the crack propagation and failure mechanism of masonry infill walls with openings.

2. Material and methods

2.1 Determination of damage characteristic

The four damage states of infilled frame without opening were described according to the story drift as DS1 (light cracking), DS2 (extensive cracking), DS3 (corner crushing) and DS4 (collapse) [3][4]. In DS1, the diagonal cracking (less than 1mm crack width) occurs on the infill panel. In DS2, the crack formation develops from DS1. The crack width is between 1 mm and 2 mm and affect over 20% of panel. Significant sliding in the mortar joints occurs in DS3. The frame is damaged and cannot be used again in DS4 [3]. Chun Hui Liu's study categorized the damage states of infilled frames by analyzing the damage description and the mechanical properties of the infill walls. This classification was derived from the extent of cracking, the damage to blocks and mortar, in-plane loads, and displacement [5].

The levels of damage can be clarified depends on the consequences of damage such as necessary repairs to structural or nonstructural components, degradation of expected performance under future earthquake and life-safety implications associated with falling hazards, fire, blocked egress, etc. Three damage states related to necessary repairs of damage were presented as minor damage (repair involving some re-taping, spackling, and re-painting of the wall), moderate damage (require replacing of selective wall boards plus the repairs) and severe damage (replace of the wall) [6] . FEMA273, three performance levels in accordance with damage are described as immediate occupancy performance level, life Safety performance level and collapse prevention performance level [7].

Predicting the type of failure that will occur in infilled frames is challenging, as it depends on various factors. Masonry infilled frames exhibit different failure modes, which can be categorized into five distinct types, as identified by [8], [9] through extensive experimental and analytical research conducted over the past five decades. The occurrence of these failure modes is influenced by the material properties and the stress state induced in the infill panel. Another significant study on the failure modes of infilled frames was conducted by [10]. Former researchers observed that that only the first two modes, namely the (CC) and (SS) modes, are of practical significance [8]. The third mode, (DC), is rarely encountered and typically associated with a high slenderness ratio of the infill, which is uncommon in practical applications where panel dimensions are designed to meet acoustic isolation and fire protection requirements.

The frequently observed in-plane failure modes encompass sliding along mortar bed joints, diagonal cracking through masonry units, step cracking or sliding along mortar joints, and toe crushing. Commonly recognized failure patterns for masonry infills are depicted in Figure 1 [11]. It can be suggested that damage states in infilled frames can be classified by measuring crack widths, which are then correlated with the proposed IDR threshold values [12]. In Table 1, the damage states of the infilled frame classified by the four researchers and FEMA are described by considering the description of the damage and mechanical properties of infill walls [3], [5], [7], [13], [15] .

Table 1: The damage states the definition of infilled frame in some researchers and code

Performance Level	IDR (%)					
	Cardone	Chun Hui Liu	Chiozzi	Kalman Sipos	Hapsari	FEMA273
DS1	0.06-0.46	0.1	0.125	<0.1	0.17	<0.1
DS2	0.21-1.38	0.3	0.327	0.1-0.3	0.52	0.1-0.3
DS3	0.5-1.98	0.9	0.82	0.3-0.75	0.79	0.3-0.6
DS4	1.06-3.26	1.9		⩾0.75	1.99	⩾0.6

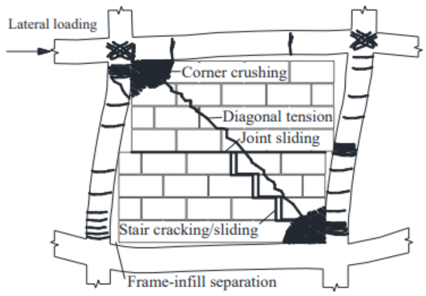
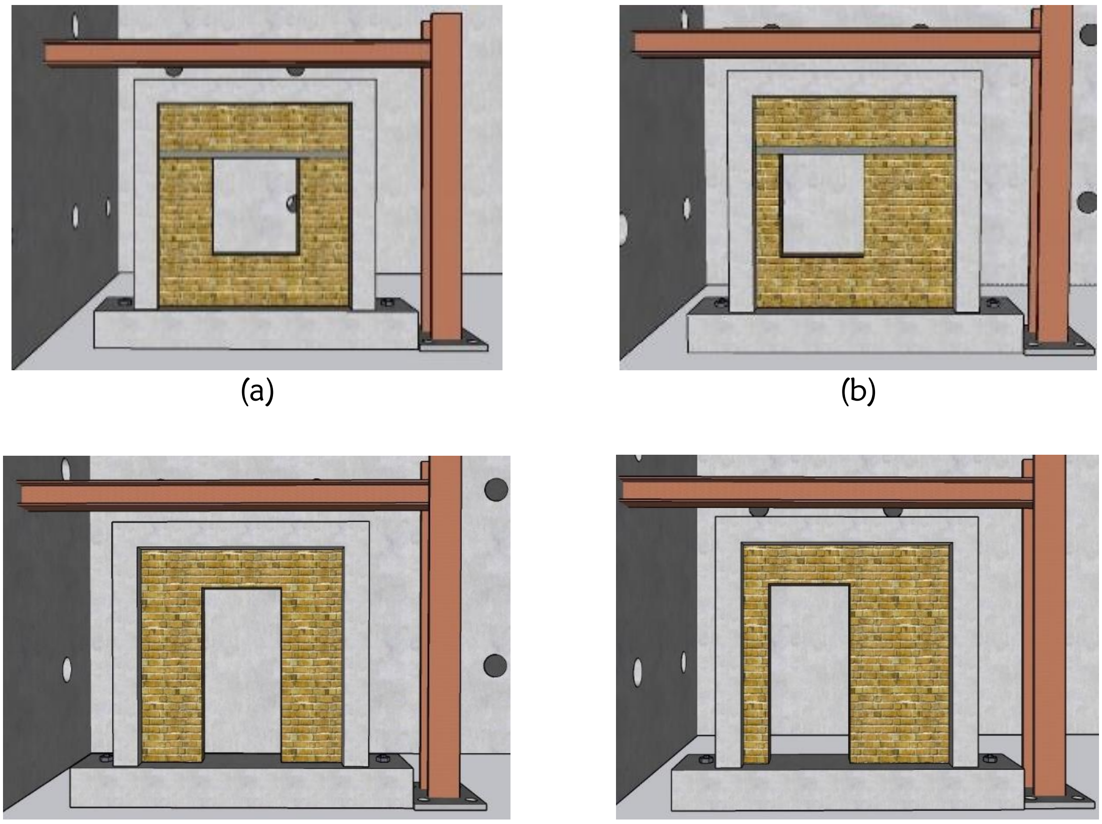


Figure 1: Typical masonry infill wall failure modes

2.2 Experimental program

In this study, the four tests were conducted to study the lateral response of infilled frame with the different size and location of opening in infilled frame. The window opening of (457 mm x 610 mm) and the door opening of (419 mm x 1067 mm) were located at the center and at the edge as described in Figure 2. The lateral load is applied at the top corner of the column monotonically and the crack propagation of frame was recorded by digital monitoring.



(a) (b) (c) (d)

Figure 2: Configuration of the infilled frame. (a) Infilled frame with central window (CW), (b) Infilled frame with eccentric window (EW), (c) Infilled frame with central door (CD), and (d) Infilled frame with eccentric door (ED)

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2.2.1 Specimens

The four half-scaled frames were tested to measure the lateral response of infilled frame due to the different opening parameter and location as centrally and eccentrically. The dimension of the frame was measured as 1200 mm long between the center of columns and 1350 mm high above the based beam. The reinforced concrete frame was constructed as detailed description shown in Figure 5. The hand-made clay brick was used to construct the masonry wall and the half-scale brick (108.3 mm x 50.8 mm and 31 mm) was obtained from cutting of full-scale brick. The preparation of mortar which is composed of 1 part of cement by 3 parts of sand was controlled and it was observed that the water-cement ratio varied from 0.7 to 0.8 for various mixes to obtain workable mortar. The 32 layers of brick work for masonry wall is built with 7 to 10 mm thickness of mortar layer for longitudinal and transverse joint.

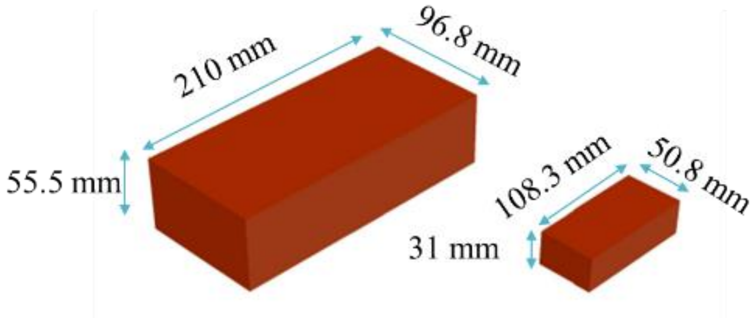

Figure 3: Dimension of brick unit (full scale and half scale

Figure 4: Construction sequence of the wall assemblies

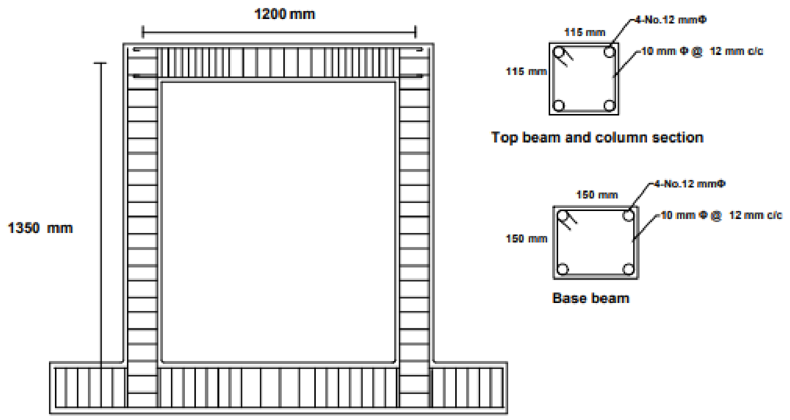

Figure 5: Reinforcement detailing of reinforced concrete frame

The material properties of concrete, reinforced steel, brick unit, mortar and masonry were carried out by using ASTM standard. The mean compressive strength of concrete was 16.4 MPa. Yield strength of longitudinal and transverse steel was 597 and 440 MPa, respectively. The compressive strength of brick unit and mortar were 10.45 MPa in half-scale and 12.03 MPa whereas the compressive strength of masonry prism was observed as 4.17 MPa which is similar with masonry prism in full-scale. The other properties including flexural strength, tensile strength and tensile bond strength of masonry were presented in Table 2.

Table 2: Material properties of brick unit, mortar and masonry

	Description	Brick unit	Mortar	Masonry
Geometric	Length (mm)	108.3	-	-
	Width (mm)	50.8	-	-
	Height (mm)	31	-	-
	Volume (10^3 mm^3)	170.76	-	-
Properties	Density (kg/m^3)	1426	1935	-
	Water absorption (%)	18.46	-	-
	Compressive strength (MPa)	10.45	12.03	4.17
	Flexural strength (MPa)	1.94	5.01	-
	Tensile strength (MPa)	-	1.55	-
	Tensile bond strength (MPa)	-	-	0.30
	Modulus of elasticity (MPa)	1860	6500	2530

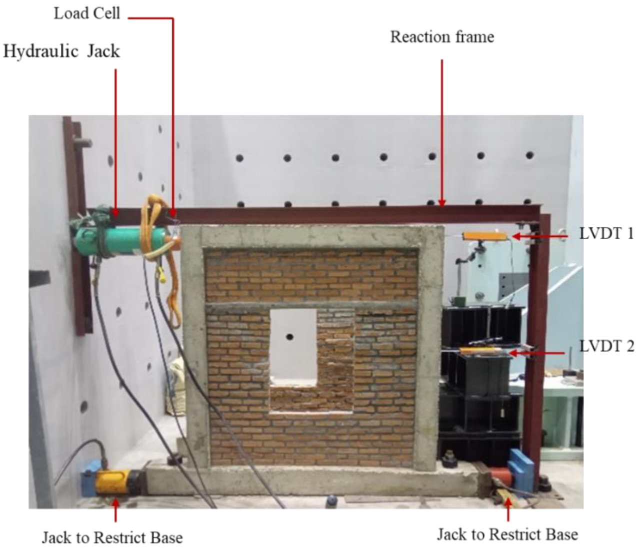

Figure 6: Test setup of infilled frame

2.2.2 Test setup and instrumentation

To determine the performance of masonry infilled wall under lateral load condition, the hydraulic jack was used to apply lateral load at upper left corner of frame as shown in Figure 6. The base member was considered as the foundation of the frame and attached firmly with the base slab of laboratory room by using bolt connection. The two LVDTs were set up top and midpoint of frame to measure the lateral displacement. The load was applied monotonically to reach the crushing failure using a 500kN hydraulic jack. A 12.5 mm steel plate was placed between frame and hydraulic jack to avoid stress concentration.

Table 3: Proposed definition of damage states of infilled frame

Performance Level	Proposed		
	Panel Failure Definition	Panel Crack Width (mm)	State
DS1	Small crack	0.01	First yield
DS2	Diagonal cracks are starting to connect	0.22	Elastic-Plastic
DS3	Cross-shaped cracks and block damage	0.69	Ultimate

3. Results and discussion

3.1 Damage states of infilled frame with opening

A load-displacement response has been observed as shown in Figure 7. It must be pointed out that the lateral load capacity of infilled frame with eccentric opening is higher than the corresponding ones with central opening. The appearance and the propagation of cracking was also recorded.

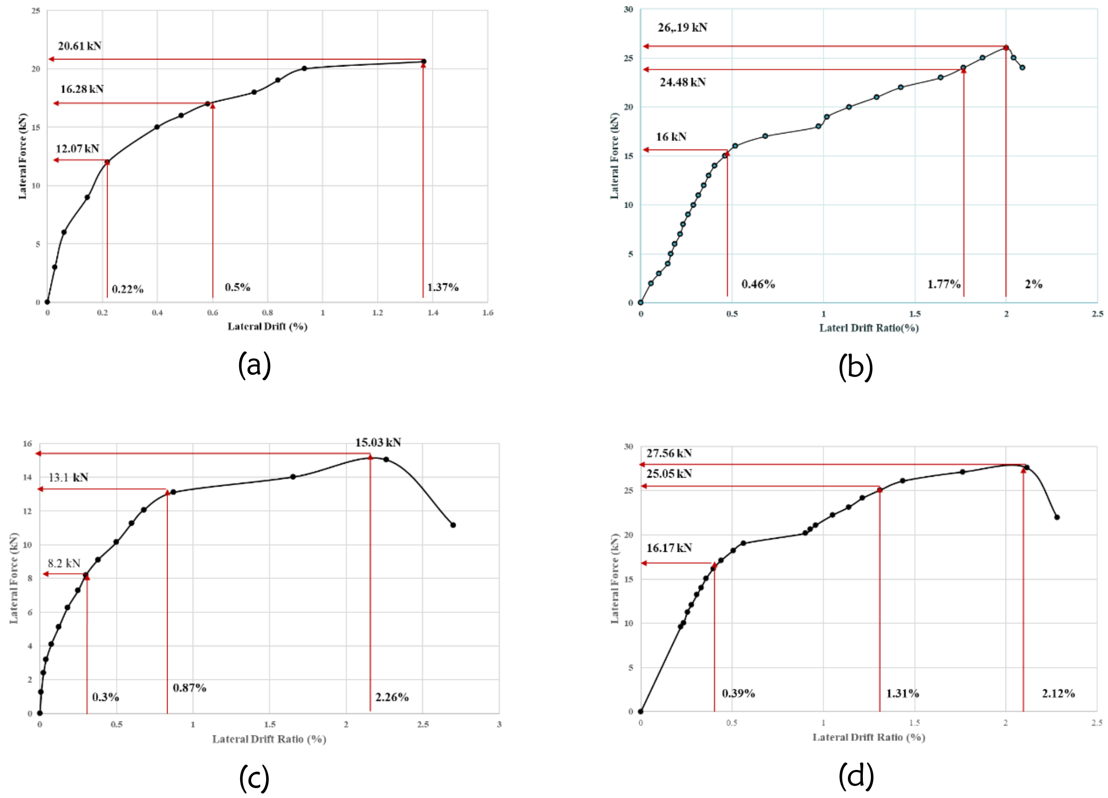

Figure 7: Capacity curve with damage state description. (a) CW Frame, (b) EW Frame, (c) CD Frame, and (d) ED Frame

The four tests were performed to observe the behavior of infilled frame under lateral force. In the first frame including central window opening, the lateral drift ratio at the maximum lateral load of 20.61 kN was 1.37. At the lateral force of 12.07 kN at the drift ratio of 0.2%, the DS1 occurs as the hair line crack on the masonry wall starts from lower corner of opening on the side away from the loading applied face. This is due to the shear failure in the unit/mortar bond area. It is stated as DS2 that the hair line crack extends diagonally on the surface of masonry between the windward column and opening as shown in Figure at 0.5% of drift ratio and 16.28 kN. At the upper left corner of the infill wall near windward column, the diagonal crushing which is crushing and splitting failure in the units (DS3) occurs at 1.37% drift corresponding with 20.61 kN.

The second test on the reinforced concrete frame with an eccentric window opening was conducted in a manner similar to that of the first sample. The opening was positioned near the column, and a monotonically increasing lateral force was applied. When the applied load reached 14 kN, the displacement of the infilled frame measured 5.56 mm, corresponding to a drift ratio of 0.4%. At this load, a diagonal crack initiated from the upper opposite side of the loaded face. Diagonal crushing began at the loaded corner, extending towards the top opposite corner of the window and continuing to the

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leeward column. Complete failure of the masonry wall occurred under a lateral load of 24 kN and a lateral drift of 2%. At a drift of 2.91%, corresponding to a load of 25.74 kN, inclined crushing of the column was observed just above the base foundation beam. Crack propagation in both the CW and EW frames is illustrated in Figures 6 and 7.

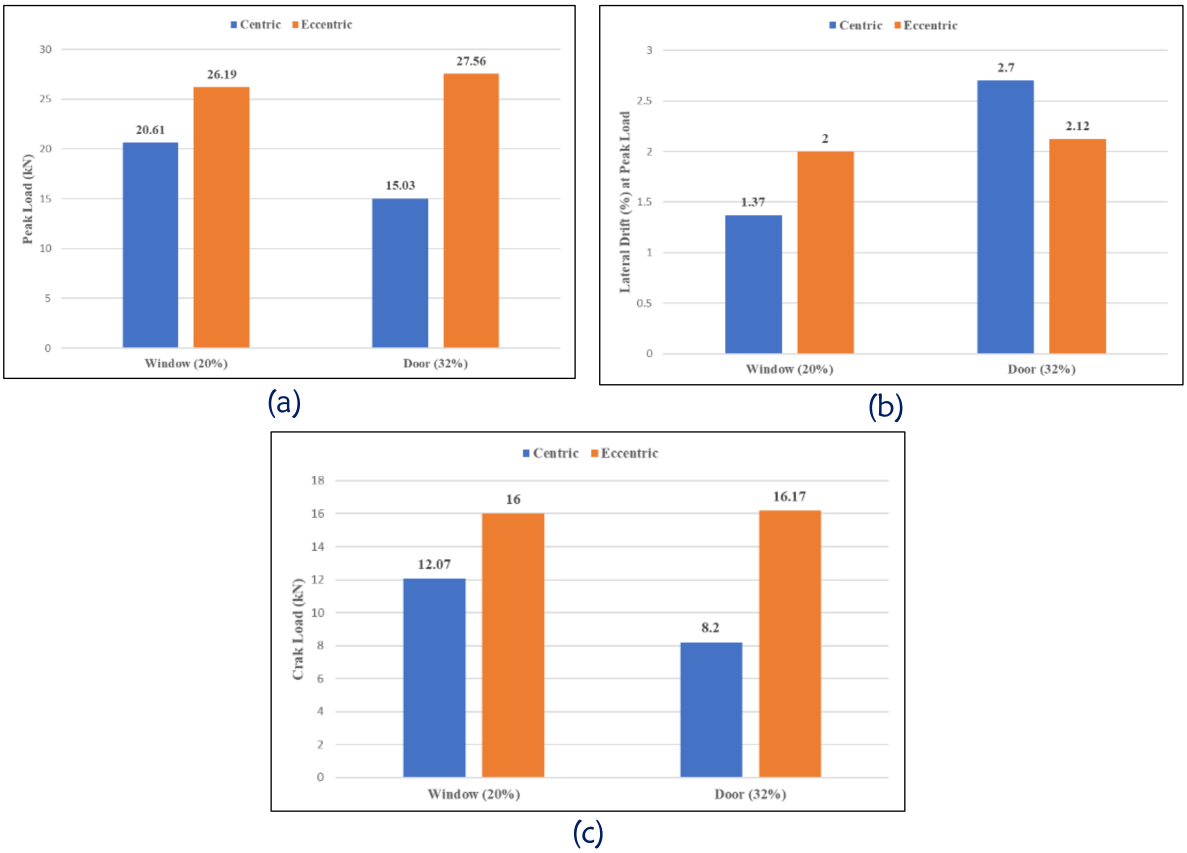

Figure 8: Comparison of peak load, lateral drift at peak load and crack load

The third test on the infilled frame with a central door opening was conducted to evaluate the lateral response resulting from an increase in the opening percentage from 20% to 32%. Three distinct damage stages were identified at lateral drift ratios of 0.3%, 0.87%, and 2.7%. The initial damage, characterized by the appearance of a hairline crack, occurred at a lateral force of 8.2 kN, representing 70% of the capacity of the frame with a central window. Following this, a significant connection between the crack and a diagonal line was observed at a lateral force of 13.1 kN. The maximum force of 15.03 kN resulted in the crushing of the masonry panel, which corresponds to the third stage of damage (DS3).

Upon completing the testing of the final frame with an eccentric door opening, the maximum lateral capacity was recorded at 27.56 kN. Three distinct damage stages were observed at lateral drift ratio of 0.39%, 1.31% and 2.12%. The first damage, corresponding to drift 0.39%, occurred under a lateral force of 16.17 kN. The second and third damage appears at the 25.05 kN and 27.56 kN of lateral force respectively.

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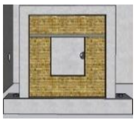
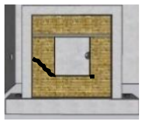
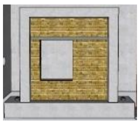
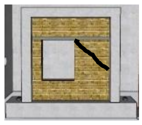
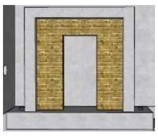
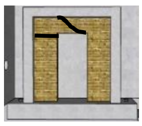
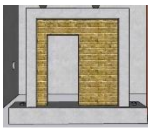
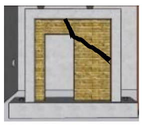
These results indicate that the lateral capacity of the frame with an eccentric door opening exceeds that of a frame with a central door opening. In comparing the results, the peak load decreases from 20.61 kN to 15.03 kN as the central opening area increases from 20% to 32%. The lateral drift is observed to be 1.37% in the masonry wall with a central window opening and 2.7% with a central door opening. The initial crack appears earlier in the frame with a central door opening, occurring at 8.02 kN, which is approximately 60% of the value for the frame with a central window opening. However, there is no remarkable difference in the three parameters of peak load, lateral drift at peak load, and crack load.

Table 4: Damage and crack pattern of infilled frame with different opening parameter and location

Wall	Description	Crack Load (kN)	Deflection, mm	Initial stiffness, kN/mm	Crack pattern
CW		12.07	3.24	1.74	
EW		16	5.56	2.14	
CD		8.2	4.76	1.57	
ED		16.17	5.44	1.62	

The comparison of opening positions reveals that the initial crack in the CW frame begins at 12.07 kN (58.56% of the peak load), whereas in the EW frame, it occurs at 16 kN (53.84% of the peak load). Following the yield point, crack propagation progresses more rapidly in the CW frame than in the EW frame. Additionally, the ultimate load capacity is greater in the CW frame compared to the EW frame. The similar result can be seen in CD frame and ED frame. A more significant result can be seen in door opening with different positions In the ED frame, the forces corresponding to the three conditions—hairline cracking, noticeable crack formation, and crushing—are approximately twice those in the CD frame. It can be concluded that the position of the opening has a more noticeable effect as the percentage of the opening increases. From the stiffness at the first major crack in Table 4, it can be concluded that the loss o stiffness is greater in eccentric opening.

3.2 Initial Stiffness

The initial stiffness is defined as the slope of the initial linear portion of the response curve. The response curve began to show non-linearity before the first visible crack indicating some initial cracking formed in either masonry infill or frame which may not be visible. The initial stiffness is more in eccentric opening. It can be seen that the opening approached the center resulted in reduction of stiffness and strength with lower ductility of the infilled specimen. More specifically, as the window opening approached the edge, specimen EW frame showed a 20% greater initial stiffness than specimen CW frame and more than doubled the latter’ s ultimate stiffness. In the case of strength, the ultimate load increased by about 80%. In CD and ED frame, the initial stiffness does not differ obviously.

3.3 Modes of failure

The crack pattern observed in the infilled frame specimen with a central window opening is depicted in Table 4. The failure modes identified include diagonal cracking between the lower corner of the window and the tension column. This failure mode is commonly referred to as the diagonal cracking mode [8], [15],[16] and is typically associated with a weak frame and a relatively strong infill. The initial major diagonal crack on the panel, located near the loaded face and sliding beneath the lower corner of the window opposite the loaded face, was observed at a drift of 0.2%. It can be seen obviously in both frames with centrally window and door opening that the most vulnerable segment is near the windward column. A great sliding damage occurs in CD frame shown in Table 4.

In the case of the infilled frame with an eccentric window opening and a door opening, splitting was observed at the top corner of the opening away from the loaded face, propagating diagonally downward. This crack development can be attributed to the predominance of normal compressive stress over shear stress. The concentration of shear stress on the segment between the loaded column and the opening led to a bed joint sliding failure.

4. Conclusion

The results in the testing of four frames with central and eccentrically opening shows that an increase in the opening percentage from 20% to 32% results in 37% reduction of lateral load capacity in frames with central opening. There is a marked reduction in lateral load capacity in frames with central openings although the frame with eccentric opening does not change significantly. It can be said that the location of the opening greatly influenced upon the lateral response of structure. Similarly, in the investigation of damage characteristic, it states remain consistent in varying opening percentages when they are notably affected by the location of the opening. All of the frames exhibit the first damage state at a lateral drift ranging from 0.2% to 0.4%. Even so, the distinct differences in damage behavior are observed that the frames with central openings showing first damage at 0.5% to 0.87% drift and eccentric openings exhibiting at over 1% drift. The frames reach the third damage state, characterized by wall crushing, at approximately 2% lateral drift. When the opening is positioned as close to the edge of the infill as possible, the performance of the infilled frame improves.

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Declarations

Author contribution

Khin Su Su Htwe: Conceptualization, methodology, project management, supervision, reviewing and editing. Hsu Nandar Htun: Conceptualization, methodology, experimentally investigated, writing the manuscript reviewing and editing.

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Conflict of interest

The authors declare no conflict of interest in this research and publication.

Ethical Clearance

This research does not involve human subjects.

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