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Experimental investigation of the infill response under the inter-story drift level for different opening location

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Abstract: This paper investigates the response of infilled frames associated with inter-story drift ratio considering the central and eccentric window opening under the in-plane force. The behavior of the structure was studied by experimental and numerical approach. Experimental results show that the lateral load capacity in eccentric window frame (EW) is 1.17 times of central window frame (CW due to interruption of diagonal loaded action by the central opening. The elastic condition of CW frame and EW frame is obtained at lateral drift of 0.2% and 0.4% respectively. As a result of weak mortar interaction, the diagonal action of crack distribution emerges along the corner of the panel in testing A numerical simulation was performed and validated with experimental results. As the comparison of results, the elastic limit points coincide between the two approaches of numerical and experimental. However, the slightly difference occurs at the peak point. The similarity can be seen in the range of 80% to 100% in the value of peak load and displacement at peak load. The numerical investigation revealed that the highest stress distribution occurred along the diagonal axis, aligning with the results of the experimental investigation.

Keywords: Sustainable cities and communities; Mitigation and disaster risk reduction; Lateral drift; Diagonal action of crack

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1. Introduction

Most of the buildings have been constructed by using reinforced concrete frame with masonry infill wall. Such masonry infill wall does not affect significantly on the structural response under gravity load; however, the compression struct action of infill wall occurs under the lateral loads due to wind or earthquake (Lee et al., 2021). This clearly shows that it needs to investigate the performance of structural frame including infill wall. Several researches were performed experimentally to evaluate the stiffness and strength of the frame, failure mechanism and damage characteristic with various loading conditions (e.g, table shaking, cyclic and quasi-static, etc.) (da Porto et al., 2020; Furtado et al., 2020; Kakaletsis & Karayannis, 2007; Milijaš et al., 2023; Nour et al., 2022; Okail et al., 2016; Pallarés et al., 2021; Zhou et al., 2018). The studied period and associated cost of experiment is a critical consideration to make the investigation and evaluation of infilled frame considering the different parameters. Moreover, due to the complexity and uncertain variables of mechanical properties of materials involving concrete, steel, mortar and brick, it offers a great challenge to get the precise findings of inquiry reliable with experimental results.

Many researchers proposed the analytical techniques to account for the interaction of frame and infilled wall to avoid more expensive cost of experiments (Anić et al., 2020; Hapsari et al., 2023; Okail et al., 2016; Pallarés et al., 2021; Sarhosis & Lemos, 2018). To develop the analytical tools for reinforced concrete infilled frame, the acceptable validation of analytical results will be made through laboratory tests. The uncertainties of properties of brick wall, aspect ratio of wall, size and position of openings, support condition and precompression correlate with the structural reinforced concrete frame (Surendran, 2012). The variable position, size and geometry of the openings were considered to study the response of frames to lateral load. The proposed analytical techniques are still in the process of transformation and progress and still studied continuously due to the complexity of the problem.

The three approaches namely micro-modeling, meso-modeling and macro-modeling can be used for modeling of masonry walls in finite element analysis. In micro technique, the masonry wall is modelled by masonry units (brick, stone, etc.) and the mortar are modelled separately and the contact surface between two elements can be modelled as interface element. In meso-modeling technique, the brick units are modelled as continuum element and mortar joints are considered as interface element. The composition of brick unit and mortar as homogeneous continuum element is utilized in macro-modeling (Ghiga et al., 2020; Houda et al., 2018; Lourenço & Rots, 1997).

This study investigated the behavior of infilled frames due to the lateral force by experimentally and numerically. The two frames with central window and eccentric window were tested to perform the opening effect on lateral drift of infilled frame. The three dimensions of nonlinear analysis using a detailed micro-modeling of infill wall was also carried out by Ansys. In the numerical simulation, solid elements with bond contact interface were created by using nonlinear material properties. The three parameters (displacement at peak load, peak load and initial stiffness) were described to validate with experimental results. The crack propagation observed in the experiment was compared with the stress distribution from the analytical results.

2. Material and methods

In this study, the two tests were conducted to study the lateral response of infilled frame with the different locations of opening. The window opening (457 mm x 610 mm) was located at the center and at the edge as described in Figure 1. The lateral load is applied at the top corner of the column monotonically and the crack propagation of frame was recorded by digital monitoring.

2.1 Speciments

Two single bay reinforced concrete infilled frames with half-scale brick unit and mortar were prepared for lateral load testing. Parametric evaluation was performed considering with different opening locations. The infilled frame had the height to length ratio of 1.125 as the height of the frame from top of the base foundation beam was 1350 mm and length of frame was 1200 mm from center to center. The reinforced steel was installed as the described dimension and design. The reinforced concrete frame was constructed as first and brick masonry infill wall was made secondly. The half-scale brick was obtained from cutting of full-scale brick and the similarity validation

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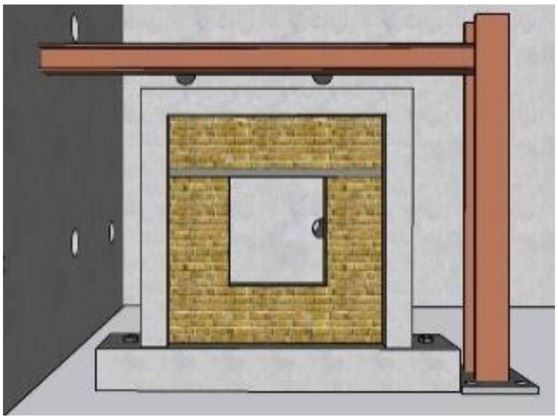
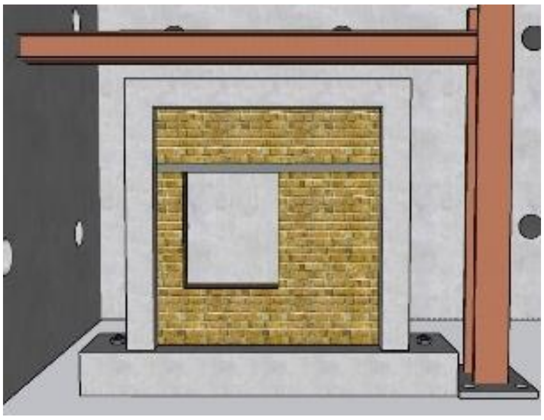
of the properties was conducted in accordance with the experimental investigation. The 32 layers of brick with 7mm thickness mortar were assembled to create the masonry wall in reinforced concrete frame. The window size of (457 mm x 610 mm) which is 20% opening area was considered for opening effect in masonry infilled wall. To obtain the variable performance due to the location of opening, the two conditions of central and eccentric perforation were carried out.



(a)



(b)

Figure 1. Configuration of the infilled frame. (a) Infilled frame with central window (CW) and (b) Infilled frame with eccentric window (EW)

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 2. 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.

Figure 2. Test setup of infilled frame

2.3 Numerical investigation

The finite element analysis has been used to study the structural performance of reinforced concrete frame including the infill wall instead of experimental evaluation. To minimize the cost of experiments, it is a powerful tool to capture the response of structure. In this respect, the detailed finite element analysis will be conducted in this study and the simulation result will be validated with experiment result.

3.1 Details of Masonry-infilled frame specimens

To simulate the in-plane behavior of unreinforced masonry wall in the reinforced concrete frame, 3D non-linear micro modeling was conducted as the bricks and the mortar were modelled separately. Unit-mortar joint interface of masonry were modelled by contact/interface elements.

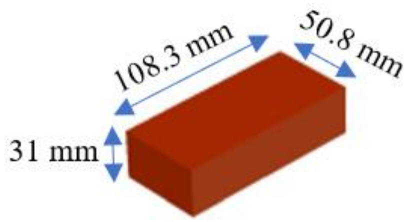


Figure 3. Dimension of brick unit

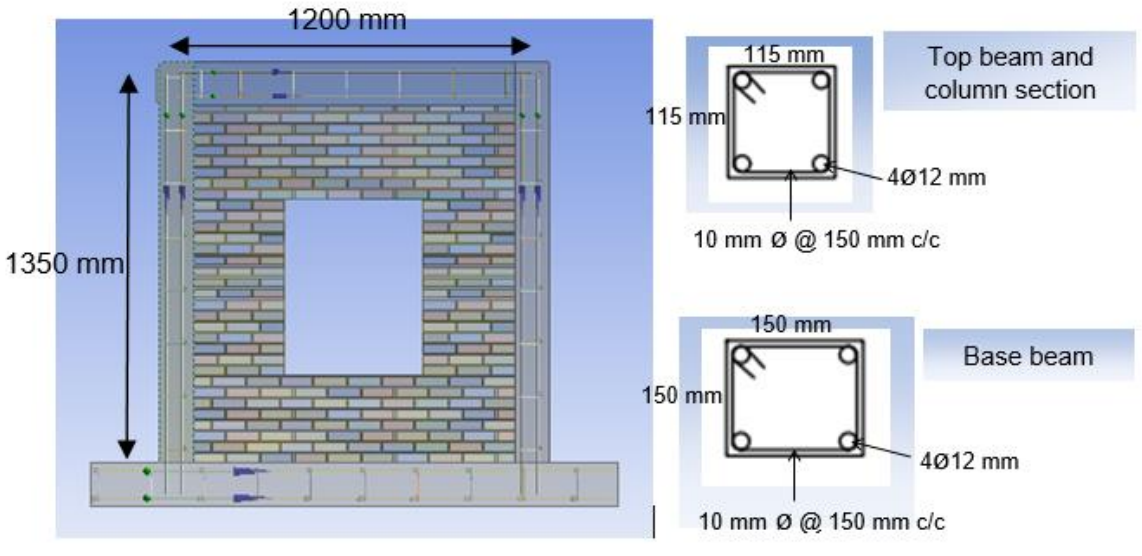


Figure 4. Section detail of infilled frame

Figure 4 shows the configuration of the infilled frame with section details. The dimension of the frame was 1350 mm height of the story from the top of the base to center of the top beam and 1200 mm length between the center to center of the column. The column was 115 mm x 115 mm in cross section and reinforced with four number of D12 bars (12 mm diameter) in longitudinal direction and D10 bars (mm diameter) stirrups at spacing of 150 mm. For the beam, the cross section was 115 mm x 115 mm and reinforced with each two D12 bars were used for flexural reinforcement at top and bottom and D10 bars (10 mm diameter) stirrups at spacing of 150 mm. For infilled frames, the bricks of 108.3 mm x 50.8 mm x 31 mm described in Figure 3 were used in masonry infilled wall and the thickness of bed and mortar joints was 7 mm similar as the experimental specimen.

3.2 Model simulation for analysis

The finite element analysis was implemented by using ANSYS 2020 for modelling of infilled frame. For the reinforced concrete frame members including the base, the higher order 3-D 20-node solid element (SOLID186) was used to model that exhibits quadratic displacement behavior. The reinforced bars were modeled as Reinf264 element and its base element share the same nodes and element connectivity. To represent contact and sliding between the surfaces of 3D elements, the bond contact element of CONTA174 element was used to simulate three interface levels (concrete-brick, concrete-mortar and brick-mortar (*CONTA174*, n.d.)

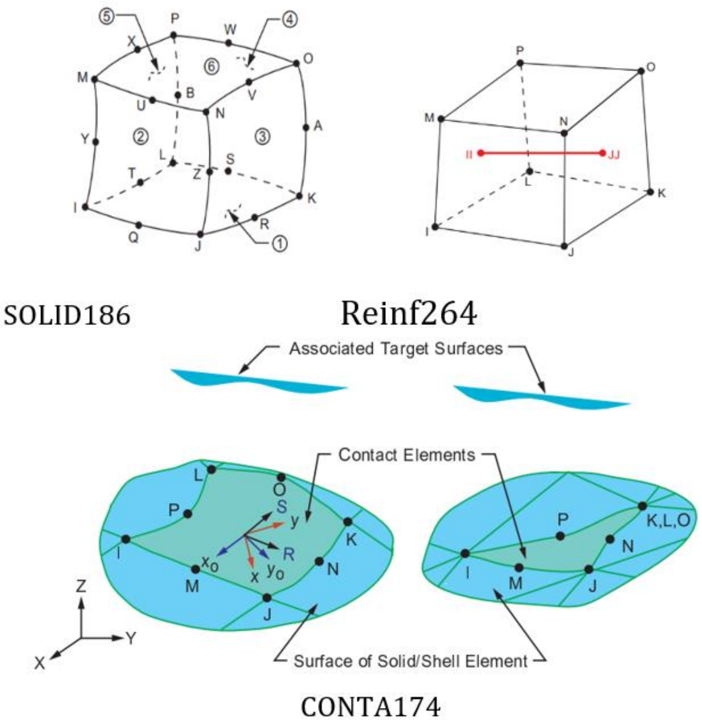


Figure 5. Elements used in numerical simulation (*CONTA174*, n.d.)

3.3 Material model for concrete and rebar

Material models of concrete used for analysis in ANSYS exit corresponding to different failure criteria, such as Von Mises, Drucker-Prager, and Menetrey-Willam. The Menetrey-willam Model is one of the most often employed concrete models in the ANSYS programme. It can capture the essential mechanical behaviour of concrete, such as different nonlinear hardening and softening behaviour under tension and compression. The strain softening due to cracking and crushing is described as a gradual decrease in strength with additional deformation. The parameters of concrete material expressed in Table 1 were applied in simulation.

Table 1. Parameters of Menetrey-Willam for concrete

Engineering Input Data in Ansys	Concrete
Uniaxial compressive strength (MPa)	16.4
Uniaxial tensile strength (MPa)	0.85
Biaxial compressive strength (MPa)	19.68
Dilatancy angle (Degree)	9

For concrete under compression, the ultimate strength of 16.4 MPa and the yield strength of 7.175 MPa was used in material strength. Wong et al., (2017) presented the details of concrete model. In Table 2, the stress-strain curve was considered using Popovics with strain (εco=0.002 mm/mm) corresponding to the peak compressive stress (fc'= 16.4 MPa). For the tensile behavior of the concrete, the tensile strength was taken as $fct=0.21\sqrt{fc'}=0.85$ MPa; before cracking, the linear elastic behavior with $Ec=4500\sqrt{fc'}=16,000$ MPa was used; the tension-softening behavior after cracking was also assumed as linear. The compression softening in cracked concrete due to transverse tensile strains was considered using the Vecchio and Collins 1986a model (Wong et al., 2013).

Table 2. Stress-strain data of concrete under compression

Stress (MPa)	Strain (mm/mm)
1.60	0.0001
7.18	0.0005
12.30	0.001
15.38	0.0015
16.40	0.002

A bilinear stress-strain curve was used for rebars. The detailed material properties are given in Table 3.

Table 3. Parameters for reinforcement

Young modulus	Poisson ratio	Yield strength	Tensile strength	Tangent modulus
2e5 MPa	0.3	368 MPa	554 MPa	2e4 MPa

3.4 Material model for unit and mortal

The properties of masonry infill including units and motor joints was considered to analyse as detailed micro-modeling. The compressive strength, tensile strength and elastic modulus of units and motor joints are obtained from experiments. To represent the behavior of masonry wall, the physical and mechanical properties of unit and mortar were defined as follows. The density of unit of 1426 kg/m^3, compressive yield strength of 3 MPa, compressive ultimate strength of 3.8 MPa, tensile yield strength of 1.5 MPa, tensile ultimate strength of 1.94 MPa and modulus of elasticity of 565.52 MPa were obtained from the experimental results.

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The properties of the mortar including bulk density, compressive strength, tensile strength and flexural strength were investigated with the specification of ASTM standards. The density of the mortar was about 1935 kg/m^3 and the compressive yield strength, the compressive ultimate strength, the tensile yield strength and the tensile ultimate strength were taken as 9.67 MPa, 10.34 MPa, 2 MPa and 2.57 MPa respectively. The modulus of elasticity of mortar was 545 MPa and the young's modulus of masonry of 2530 MPa was evaluated from the prism test.

The connection between concrete, brick unit and mortar were also modelled by using bonded contact elements of CONTA174. The meshing is essential to get the accurate results from the numerical modeling. The different mesh size of 13.5 mm for brick unit, 6 mm for mortar, 25 mm for columns and beams were considered and 228829 number of nodes and 32218 numbers of elements were obtained.

3. Results and discussion

3.1 Experimental results

The two specimens including window opening centrically and eccentrically were prepared to carry out the experiments. After finishing the instrument set up, the load is applied gradually by hydraulic jack until getting the complete damage of specimen. In the sample with centrally window, when the load reaches the value of 12.07 kN and drift ratio is 0.2%, the cracking on the masonry wall start 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. At 0.5% of drift ratio and 16.28 kN, crack line appears on the surface of masonry between the windward column and opening and connect the crack at the lower corner of opening. At the upper left corner of the infill wall near windward column, the diagonal crushing which is crushing and splitting failure in the units occurs at 1.37% drift corresponding with 20.61 kN.

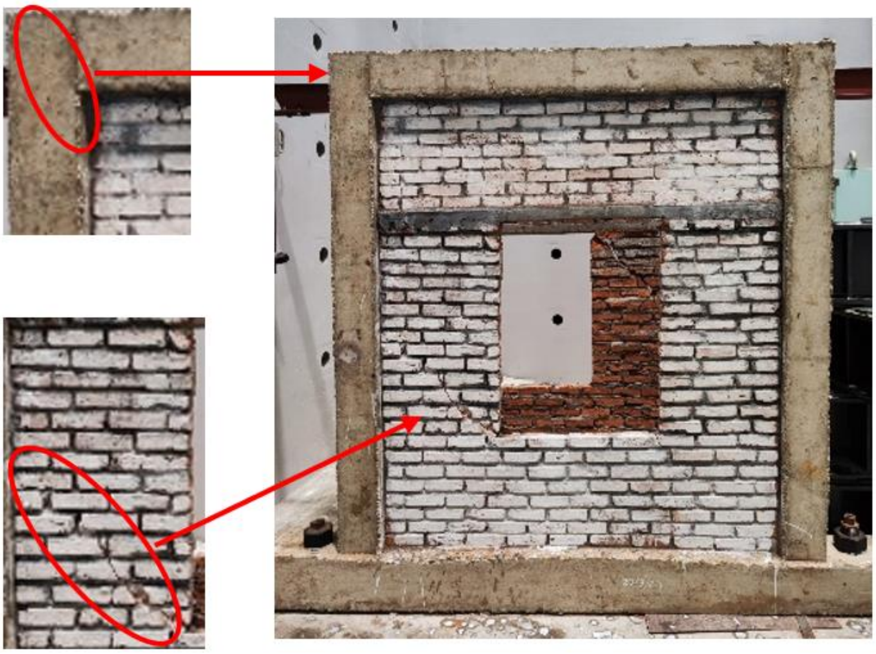

Figure 6. Crack formation of CW frame

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The second specimen of reinforced concrete frame with eccentric window opening was tested as a similar way of the first sample. The opening was located near the column and applied lateral force monotonically. At the value of applied load (14 kN), the displacement of infilled frame is 5.56 mm (drift ratio of 0.4%) and the diagonal crack initiates from the upper opposite side of loaded face. The diagonal crushing appears from the loaded corner to opposite top corner of window and extents to leeward column. Complete damage of masonry wall occurs at the lateral load of 24 kN and the lateral drift of 2. The inclined crushing of this column appears upper of the base foundation beam at 25.74 kN of drift (2.91%). The crack propagation of CW and EW frame can be seen in Figures 6 and 7.

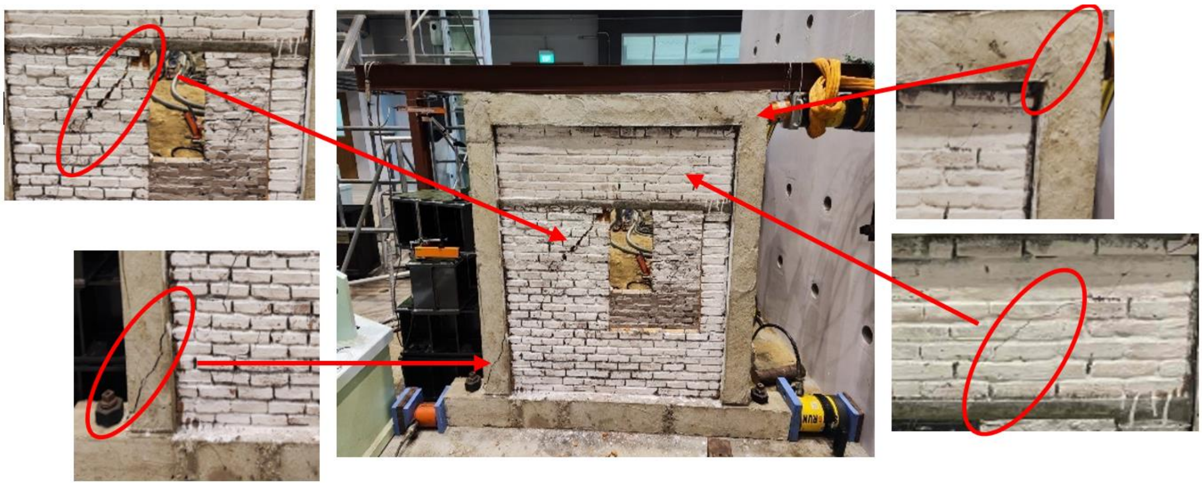


Figure 7. Crack formation of EW frame

3.2 Numerical modeling validation with experimental results

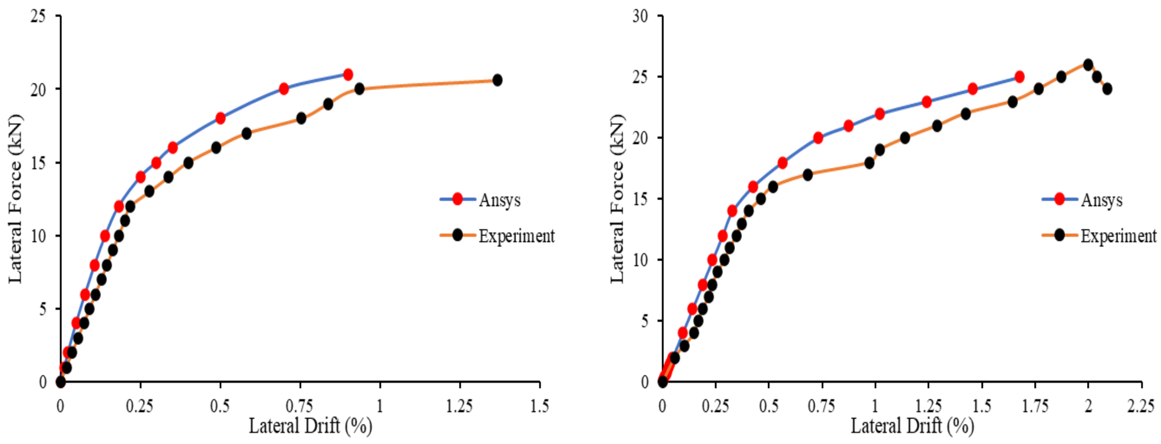
The three parameters of the displacement value at peak load, peak load and initial stiffness were considered to validate between the experimental and numerical results as shown in Table 4. In the first frame with central window opening, the displacement at peak load is 15.08 mm in numerical and 18.22 mm in experiment with similarity of 83%. The 20.61 kN of peak load is obtained from the experiment when the peak load from numerical analysis is 20 kN. The initial stiffness is obtained from the ratio of yield force and yielding displacement. In the central window opening model, the initial stiffness is 3.7 kN/mm in experiment and 4.8 kN/mm in numerical. Therefore, the similarity is 129%. The force at elastic condition and peak is nearly the same in two results while the displacement at elastic point is 4.06 mm and 3.5 mm in the experiment and analysis result respectively. In the second reinforced concrete frame with eccentric window, it can be seen that the peak load is 26 kN from experiment and 25 kN from numerical result at the displacement of 27.44 mm and 23.3 mm respectively. The initial stiffness is observed as 2.52 kN/mm in experiment and 3.1 kN/mm in Ansy. The values in the elastic region is similar and it slightly differs beyond the elastic region.

The lateral load associated with lateral drift ratio is plotted from experimental and numerical results in Figure 8. In Figure 8a, the elastic limit point corresponding to 60% of the peak strength reaches at lateral drift of 0.2% and 0.18% in these two results. The peak point occurs at drift ratio of 1.3% in experiment and 0.9% in analysis. The

P-δ curves agreed well with the test results not only in the frame with central window, but in the frame with eccentric window as shown in Figure 8b. The elastic limit point in eccentric opening occurs 61% of the peak strength at drift 0.4% in test result and 56% of the peak strength at 0.32% drift in numerical result. The peak point is observed at 2% drift ratio in experiment and at 1.7% drift ratio in analysis.

Table 4. Comparison of results

Parameters	Unit	Central window opening			Eccentric window opening		
		Experiment	Ansys	Similarity	Experiment	Ansys	Similarity
Peak load	kN	20.61	20	97%	26	25	96.15%
Displacement at peak load	mm	18.22	15.08	83%	27.44	23.3	84.91%
Initial Stiffness	kN/mm	3.7	4.8	129%	2.52	3.10	123%
Elastic Point	kN	12.07	12	99%	16	14	87.5%
Displacement at elastic point	mm	4.06	3.5	76%	5.56	4.50	80.94%

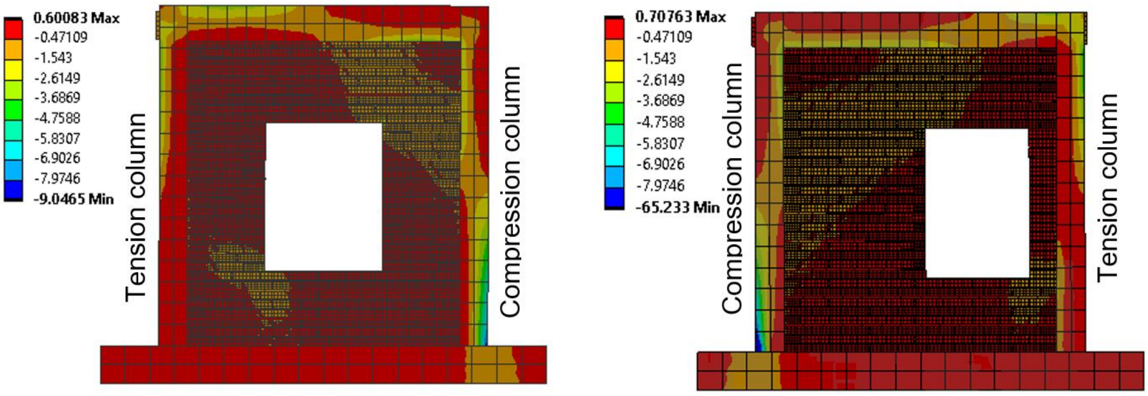


(a) (b)

Figure 8. Lateral capacity curve of infilled frame. (a) CW frame and (b) EW frame

Figure 9 shows the distribution of minimum principal compressive stresses at the peak load and the yellow color indicates the compressive stress while the red color indicates tensile stress. Upper the opening near the compression column in these two frames, the diagonal compressive stresses were almost uniformly distributed. The same distribution at the opposite bottom corner occurs and extends to the tension column. On the masonry panel of CW frame, the compressive stress distributed area expands widely between the upper corner and compression column. Similar as the CW frame, the high compressive stress in EW frame occurs along the diagonal direction between compression column and top corner of opening and extents to top beam. In this observation, the opening on the diagonal of infill panel disturbs the load mechanism of lateral response and it leads the combined failure modes of Diagonal Compression (DC) mode and Diagonal Cracking (DK) mode. The crushing within the central region of infill panel is demonstrated as Diagonal Compression (DC) mode and the diagonal compressive cracking on the panel is represented as Diagonal Cracking (DK) mode (Huang & Burton, 2019; Wood, 1978). This mode is associated with weakness of frame and joint between bricks. As a result, this numerical modeling approach can capture the load-displacement response and failure mechanism and has a good agreement with the results from experimental investigation.

(a)



(b)

Figure 9. (a) Failure mode of test result and (b) Stress distribution of analysis result

4. Conclusion

This study investigated the response of infilled frame with opening by nonlinear finite analysis. This approach of numerical modeling can capture both the lateral drift associated with lateral force and stress distribution. As the comparison of numerical result with experimental results, this numerical approach can produce structural responses that closely approximate actual behavior. The validation of this numerical approach with experiments was performed with three parameters of the displacement value at peak load, peak load and initial stiffness. The similarity in peak load and displacement at peak load was around 80% to 100% between experiment and numerical results. The local damage of infilled frame can be investigated by this numerical approach. From the testing, the crushing from bottom corner to tension column in CW frame and from top corner to compression column in EW frame can be obviously observed. From the numerical investigation, the highest stress distribution was observed along the diagonal axis, consistent with the findings from the experimental investigation.

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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, numerically investigated, writing the manuscript reviewing and editing.

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Competing interest

The authors have worked together for the development of structural performance analysis under lateral load considering the infill wall with opening. They have published several research articles in scientific societies.

Ethical Clerance

There are no human subjects in this manuscript and informed consent is not applicable.

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