VOL. 19, NO. 7, APRIL 2024 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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STRUT METHOD FOR THE ANALYSIS OF CONFINED MASONRY STRUCTURE WITH OPENING SUBJECTED TO VERTICAL AND LATERAL LOADS

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ABSTRACT

Confined Masonry (CM) is considered one of the most efficient construction systems for low-rise buildings and has demonstrated its ability to withstand strong earthquakes in various countries. However, the analysis methods for CM, especially for CM with opening, have yet to be widely agreed upon. This research proposes a method for analyzing CM with confined openings subjected to vertical and lateral loads. The proposed method combines diagonal struts with an equivalent frame and rigid zone approach (MSC). Before creating the MSC model, a validation model is developed using layered shell elements (Msh). This validation model is then expanded to incorporate different ratios of openings ranging from 10% to 30% and various positions of window and door openings, both centrally and eccentrically located. The shell model serves as a reference for the subsequent creation of the MSC model. The validation model shows that the layered shell model (Msh) can accurately mimic the behavior of CM with an opening if the elastic modulus of the concrete and masonry materials is reduced by a reduction factor of 0.1. The MSC model, having the stiffness of beams and columns of 100 and the axial area factor (Aax) varied yields a response corresponding to the response obtained from the Msh model. The CM with window openings (CWO) and door openings (CDO) with the same opening ratio exhibit different responses and, therefore, have other strut width equations. The CM with centric and eccentric window openings has the same strut width equation and axial area factor (Aax). However, for the CM with door openings, different strut width equations and axial area factors are used for centric and eccentric openings.

Keywords: combined vertical and lateral load, confined masonry, diagonal strut, shell element, CM with opening.

Manuscript Received 26 February 2024; Revised 23 April 2024; Published 30 May 2024

1. INTRODUCTION

Confined Masonry (CM) is an efficient construction system for low-rise buildings that has proven to survive strong earthquakes in many countries, such as Mexico, Chile, India, and China [1]. CM utilizes reinforced concrete beams and columns as confining elements around the walls. Construction involves building the walls first, then casting the columns and beams as confinement. The confinements enhance the wall's strength in resisting vertical and lateral loads [2]. A well-built CM with regular floor plans and adequate wall density can withstand significant earthquake impacts without collapsing and, in many cases, without experiencing significant damage [3]. Results from experimental tests and past earthquake damage investigations show that CM generally does not face issues when subjected to gravity loads but starts to experience damage when subjected to extreme earthquake loads [4]. In India, CM has been successfully implemented on a large scale in multi-story hostel buildings on the campus of the Indian Institute of Technology Gandhinagar (IITGN), including six three-story and 30 four-story buildings. Based on many scientific and observed data on the performance of CM construction, the Earthquake Engineering Research Institute (EERI) has recommended the use of CM for low-rise buildings in earthquake-prone areas [5].

Even though CM buildings have become a popular choice for low-rise residential construction in many earthquake-prone countries, they have yet to be widely used in Indonesia for multi-story buildings. However, CM is widely used for simple single-story buildings such as residential houses. Among the reasons is the need for specific design guidelines for CM in Indonesia.

Openings in CM significantly reduce the wall's performance and become critical points during earthquakes. There is evidence of damages observed around the openings, as seen in the 2010 Chile earthquake [6]. Stress concentration is observed at the opening corners, causing shear cracks that render the walls unstable and lead to failure. The shortcomings due to openings can be addressed by using confining elements around the openings. These confining elements prevent shear cracking at the opening corners and maintain the wall's stability [7].

CM has garnered considerable research interest. Several guidelines and regulations for CM construction have been developed in recent years in various countries. However, most of these guidelines are subjectively determined based on experience and apply to single to two-story buildings. Various modeling techniques have been developed for CM analysis, continuously improving methods to achieve different precision levels.

To date, few researchers have proposed analysis methods for CM, including for CM with openings and CM in multi-story buildings. The research on the Strut-and-Tie Model (STM) method has been conducted. However, this study [6] only modeled the structure using software without validating it through laboratory testing. Reports show that struts only resist either gravity or lateral loading. The wall thickness was assumed to be the same as the thickness of the tie, but the width of the struts was not provided in this research [6]. An analysis for CM using the Equivalent Frame Model (EFM), also known as the Wide Column Model (WCM), was performed, in which rigid beams were used to simulate the stiffness effect of the brick masonry. In this study, the walls were analyzed using both the Finite Element Method (FEM) and EFM approaches using the commercial analysis software SAP2000. However, this study did not reference laboratory testing and only used the macro FEM model as a reference for the analysis [8]. Borah *et al.* [9] developed the Strut Model V-D and conducted a numerical study on Light Clay Brick Wall structures with vertical and lateral loads using SAP2000 software. However, this research was limited to Light Clay Brick Wall structures with solid walls and did not include walls with openings or doors. Ajmal *et al.* [10] compared the performance of alkali-activated fly-ash-based geopolymer concrete bare frame and confined masonry wall panels with conventional concrete. Experimental results showed that geopolymer concrete bare frame has 3.5% higher initial stiffness and 1.0% higher lateral load-bearing capacity than conventional concrete. It was intended to promote construction practices that are cost-effective, environmentally friendly, sustainable, and capable of withstanding earthquakes.

Initial research has been conducted using strut methods for analyzing CM with openings, but it was limited to cases of centric openings and lateral loads only [11]. The strut model was represented by frame elements and employed rigid zones and axial area modification factors (AAX).

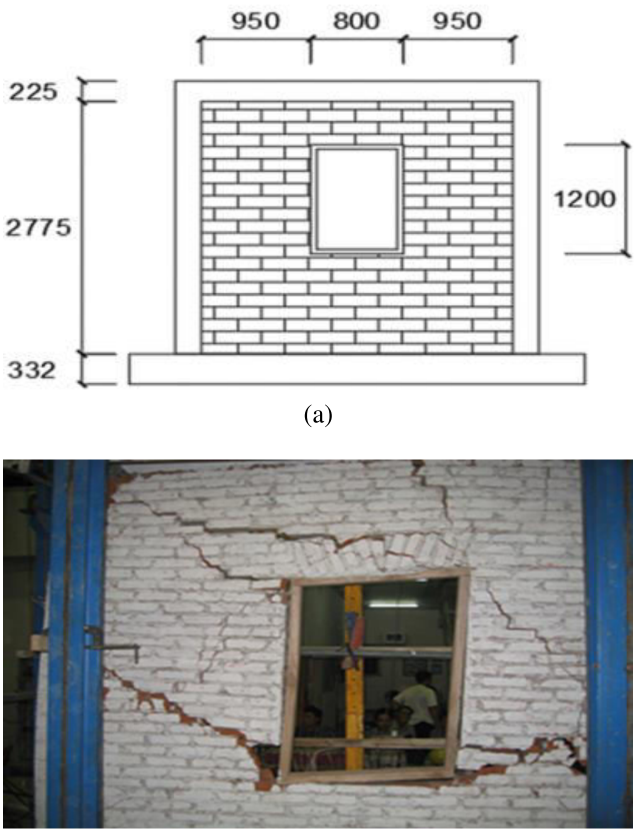
The analysis method is required to implement the CM structural system in Indonesia. This study proposes a diagonal strut method combined with rigid zones for CM with both Window Openings (WO) and Door Openings (DO). This research will observe the behavior of CM with openings under vertical loads as the assumption of multi-story building loads and lateral loads as the assumption of earthquake loads. The results of this study are expected to provide new insights into the performance and stability of CM with openings and contribute to the development of safer and more efficient structural technology and planning.

2. MATERIALS AND METHODS

The steps taken in this research are as follows:

2.1 Validating the Shell Model with Laboratory Testing

The research begins by gathering secondary data from tested CM with openings conducted by Suarjana *et al.* [12]. The data includes specimen geometry and material used to create the validation model. The testing focused only on CM's lateral load performance, so the validation model is loaded laterally without considering vertical loads. The specimen details under review are CM with a Window Opening (CM-WO), as shown in Figure-1. (a). Confining elements with 225 mm x 100 mm dimensions represent the minimum concrete area following the Ministry of Public Works guidelines. The window opening is 800 mm x 1200 mm, located in the middle of the wall, with a 13% opening ratio. A 50 x 100 mm wooden window frame is used around the opening. Figure-1 (b) shows the crack pattern of the specimen after testing.



(a)

(b)

Figure-1. Suarjana et al. (2012)'s Confined masonry with window opening (CM-WO) Testing (a) Dimensions and (b) Crack Pattern.

As shown in Figure-1, the research specimen follows standard construction practices in Indonesia. The specimen's wall is made of medium-quality concrete, red brick, and mortar. The confining material used is concrete with a compressive strength of 15,32 MPa, tensile strength (f_{tc}) of 2,298 MPa, and an elastic modulus of concrete (E_c) obtained from equation (1) by Shrikhande [13] which is 18396 MPa. The longitudinal reinforcement of D10 (*fy*: 384,9 MPa) and transverse reinforcement of d8 (*fy*: 350,9 MPa) are used. The compressive strength of brick (f_m) is 3,5 MPa, and the compressive strength of mortar (f_{cm}) is 8,74 Mpa. The elastic modulus of brick masonry (E_m) is obtained from equation (2) by Eurocode (1996) [14], which is 1740 Mpa, for the compressive strength of brick masonry (f'_m) is obtained from equation (3) by Eurocode (1996) [14] which is 2,32 Mpa, tensile strength for brick masonry (f_{tm}) of 0,414 MPa, and shear strength (vm) of 0,827 MPa.

$$E_c = 4700\sqrt{fc} \quad (1)$$

$$E_m = 750 f_m \quad (2)$$

$$f'm = 0{,}5\, fm^{0{,}65}.fcm^{0{,}25} \quad (3)$$

The validation model (Msh-CM-WO) is created using layered-shell elements in SAP2000 software. A static nonlinear pushover analysis is conducted on the validation model, controlling displacement targets to determine how much deformation the structure may experience. The analysis results include the model's load-displacement (V-d) curves and stress distribution.

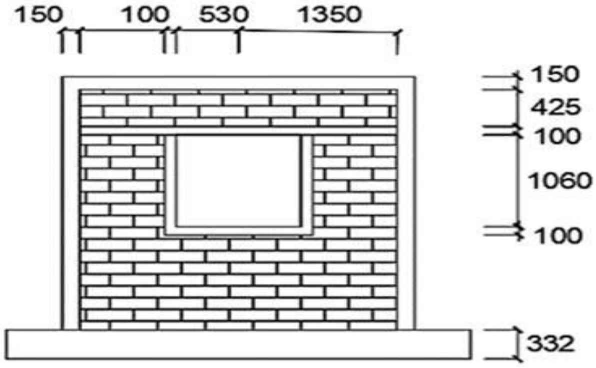
The V-d curve from the validation model is then compared with the V-d curve obtained from laboratory testing. Also, the model's stress distribution is observed to identify locations of stress concentration that may lead to cracks in the wall. This will be confirmed by the crack patterns found in the test specimens. Suppose the validation model's analysis results do not match the test results. In that case, iterations are performed in creating the validation model until its response aligns with the test results and can be considered valid.

2.2 Adding Confinement around the Opening

After successfully replicating the behavior of the test specimen in the validation model, the research continues by adding confining elements around the window openings in the validation model (CM-CWO). The confined masonry model with captive elements around both window and door openings shows 31, 2% more resistance to the seismic forces than without confined elements around the opening [15]. A continuous lintel beam with dimensions of 100x100 mm is installed entirely above the openings, encompassing the sides of the openings, as seen in Figure-2 (a). The analysis method used is the same as in the initial validation model. The analysis results, including the V-d curve and stress distribution, are compared with the behavior of the initial validation model. If the addition of confinements gives a response similar to but more robust and stiffer than that without confinement, then the model is considered adequate and acceptable.

2.3 Development of Strut Model Combined with Rigid Zone (MSC)

The research determined the initial configuration of the Model Strut Combination (MSC) for analyzing CM with openings under combined vertical and lateral loads. The dimensions of CM-CWO are shown in Figure-2. (a), and the initial configuration of MSC is shown in Figure-2 (b). Columns and beams experience increased stiffness, assuming the columns are rigid and composite with the walls through confining elements. The thickness of the struts is considered equal to the wall thickness, and the strut width is adjusted to make the MSC behavior similar to the behavior of the validated model (Msh).



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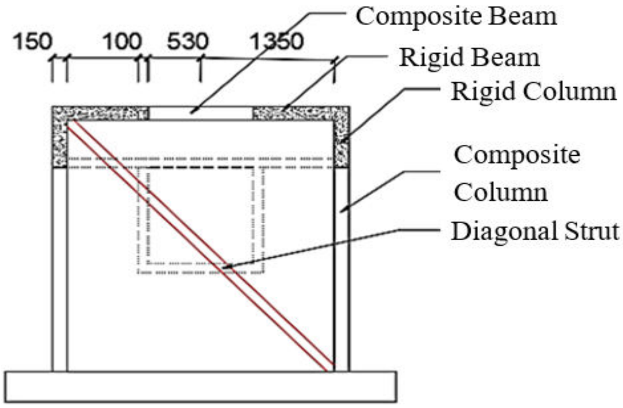

(b)

Figure-2. (a) Confined Masonry (CM) with Window Opening and (b) Model Strut Combination (MSC).

2.4 Variations in CM Models

The research phase continues by creating Msh with door openings (CM-DO) and window openings (CM-WO) with centric positions, as shown in Figure-3, and eccentric positions, as seen in Figure-4. Window openings in the wall are created with opening ratios of 10%, 15%, 20%, 25%, and 30%, as shown in Figure-3. (a), while door openings in the wall are made with opening ratios of 25% and 30% as shown in Figure-3. (b). For the CM openings, practical confinements with beams and columns are applied around the openings. Eccentric openings are positioned at a minimum distance of 600 mm from the column edge, following the guidelines provided in "Guidelines for Earthquake Resistant Non-Engineered Construction" [16].

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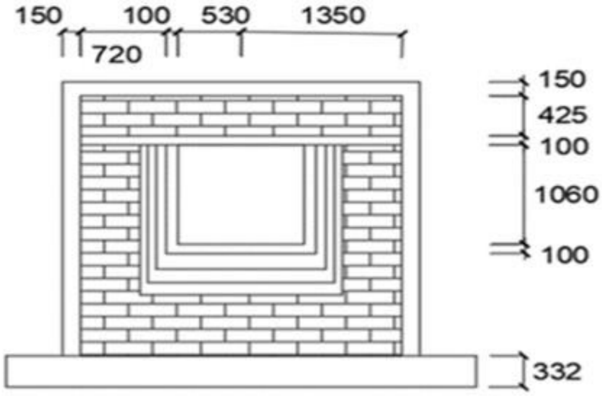

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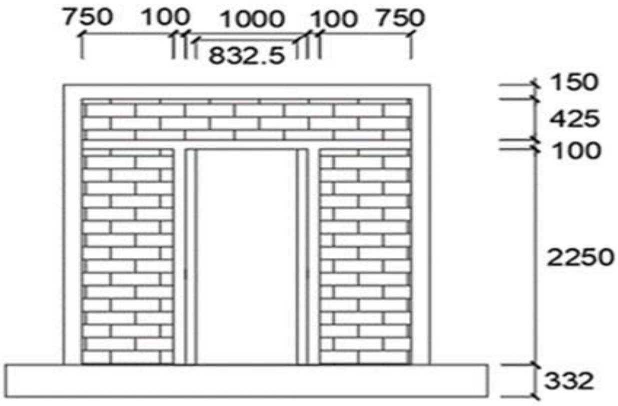
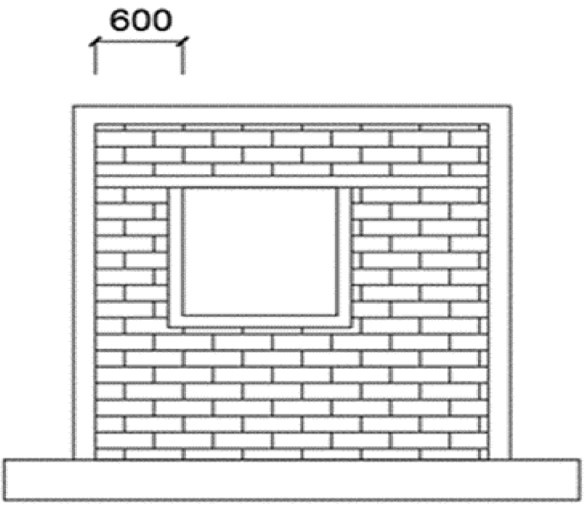


(b)

Figure-3. CM with centric openings and variations in opening ratios: (a) Window openings and (b) Door openings.



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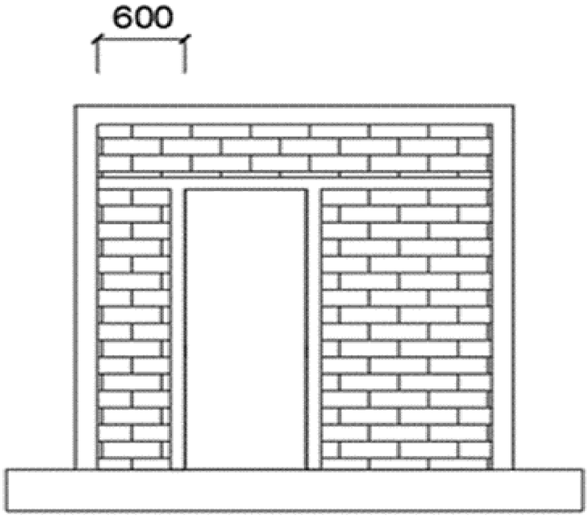


(b)

Figure-4. CM with eccentric openings: (a) Window openings and (b) Door openings.

2.5 The Strut Width Equation in MSC

Model Msh-CM-DO is compared with Model MSC-CM-DO, and Model Msh-CM-WO is compared with Model MSC-CM-WO. The width and axial area of the strut are adjusted to produce the same response. After achieving the same responses between Msh and MSC, all MSC Strut data is grouped based on the opening ratio and type. Then, these values are presented in graphical form using Microsoft Excel software to obtain polynomial regression equations.

3. RESULTS AND DISCUSSIONS

3.1 Validation of the CM-WO Model under Lateral Loading

Several property values were modified in the software to align the model curve with the test results conducted by Suarjana *et al*. (2012) [12]. These modifications are necessary because shell element models are generally stiffer than the actual models. Distorted shell element models were created as references to develop a strut model for CM with openings since insufficient testing data is available. The initial validation stage began with the unmodified elastic modulus or MShell (1E) model. During the validation testing of the shell model, it was found that the MShell (1E) model was too stiff compared to the tested CM wall. To align the stiffness with the tested CM, we reduced the elastic modulus of the brick masonry and confining concrete by a factor of 0.1E (shown as a solid red line on the graph). This modification successfully adjusted the lower part of the load-displacement curve to match the actual CM test results. This adjusted shell model is named Msh-CM-WO. The final results of the validation model Msh-CM-WO are presented in Figure-5.

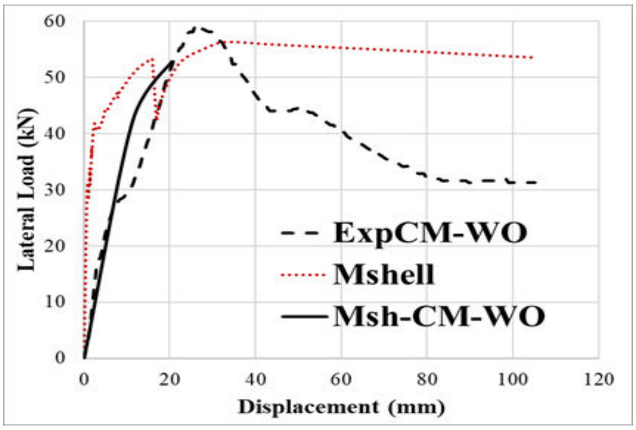
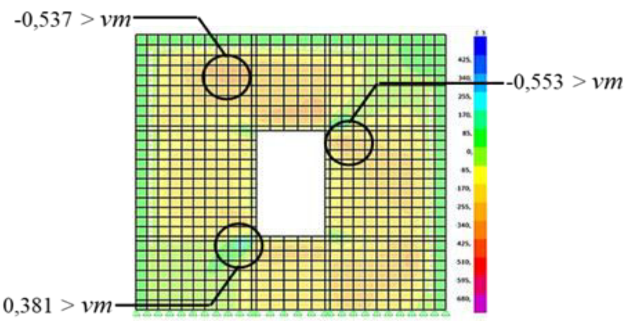


Figure-5. V-d curve of shell models vs test result.

Stresses on the wall are examined to determine the locations of stress concentrations that occur. The stress contours on the wall are shown in Figure-6 (a) and (b). Based on the SAP2000 analysis results of the Msh-CM-WO model, stress concentration occurs around the openings. The compressive stress is 1,071 MPa, which has not exceeded the compressive strength of the wall. However, the tensile stress in the wall is 0,486 MPa, which has exceeded the tensile strength of the wall, which is 0,414 MPa. Both compressive and tensile stresses are higher at the corners of the openings compared to the adjacent parts of the wall. The shear stress is 0,537 MPa with a base shear force of 57,5 kN, which has exceeded the shear strength of the wall, which is 0,341 MPa. Therefore, the failure of the wall is due to tensile and shear failures. Based on the load-displacement curve and stress distribution results, the Msh-CM-WO model exhibits behavior similar to the test results in Figure-1 (b). The Msh model serves as a reference for developing the MSC.



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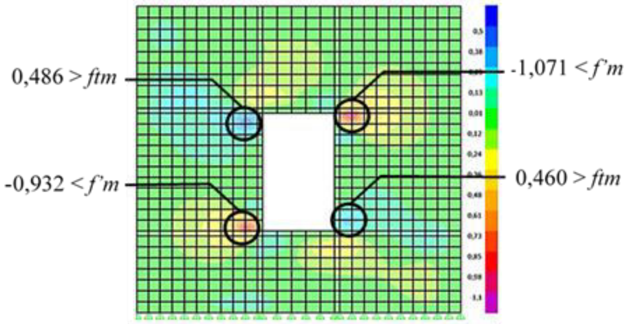


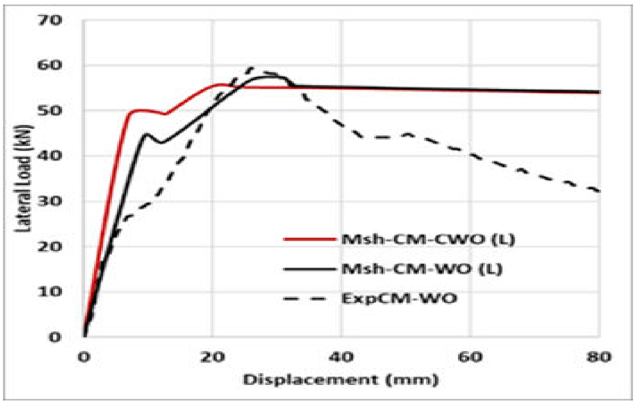
(b)

Figure-6. Stress contour on the wall of the Msh-CM-WO (Mpa) (a) S12 and (b) S22.

3.2 CM with Confinement around the Openings and Subjected to Lateral Loading

An additional model with confinement around the openings (Msh-CM-CWO) is created based on the CM-WO test model to investigate the effect of confinements around the openings. The load-displacement curve of Msh-CM-CWO is then plotted together with the Msh-WO model on the graph in Figure-7 (a) and the stress contour S22 on the confinements around the openings of the Msh-CM-CWO model is shown in Figure-7 (b). The stress contours on the wall are shown in Figure-8 (a) and (b).

After adding confinements around the openings, the stress contour shows that the stress at the corners of the openings increases up to 3, 98 MPa. The compressive and tensile stresses on the wall have decreased. The compressive stress occurring on the wall, at 0,606 MPa, does not exceed the compressive strength of the wall. The tensile stress, measuring 0,271 MPa, does not surpass the tensile strength of the wall. However, the shear stress of 0.423 has exceeded its shear strength of 0,341 MPa and is located in the constricted wall section above the lintel beam. As a result, the initial damage that occurred around the opening has been minimized.



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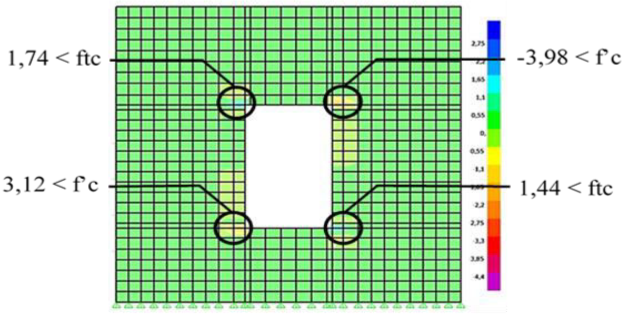
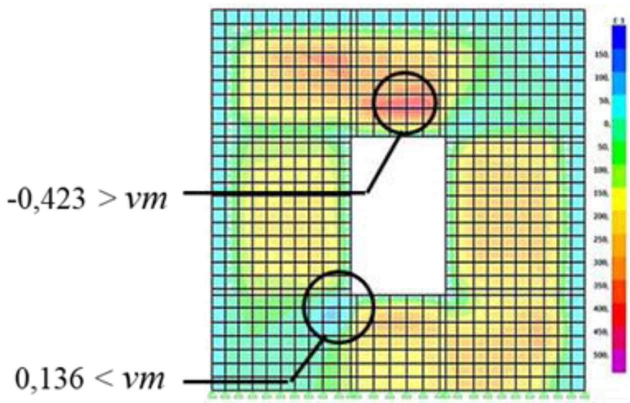


(b)

Figure-7. (a) The load-displacement curves of Msh-CM-WO and Msh-CM-CWO and (b) stress contour S22 on the confinements around the openings of the Msh-CM-CWO model (MPa).



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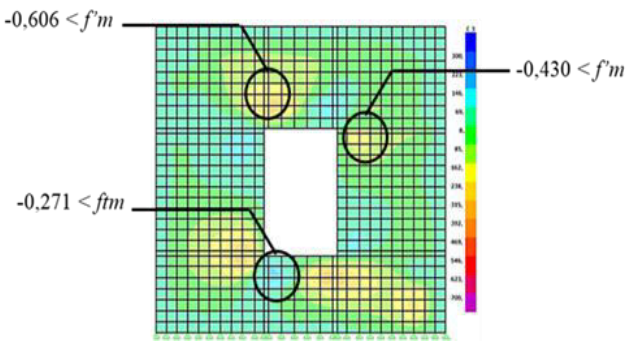
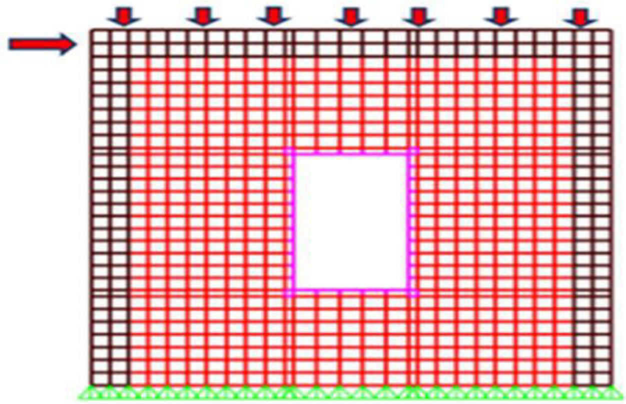


(b)

Figure-8. Stress contour on the wall of the Msh-CM-CWO (Mpa) (a) S12 and (b) S22.

3.3 CM-WO with a Combination of Vertical and Lateral Loading

To obtain behavior that aligns with CM, the Msh-CM-WO model is subjected to a combination of vertical and lateral loads such as shown in Figure-9 (a) (the red box represents a brick masonry, and the brown box represents composite columns), and this model is referred to as Msh-CM-WO (V+L). Subsequently, the load-displacement curves of both Msh-CM-WO models with different loading conditions are plotted together, as shown in Figure-9 (b).



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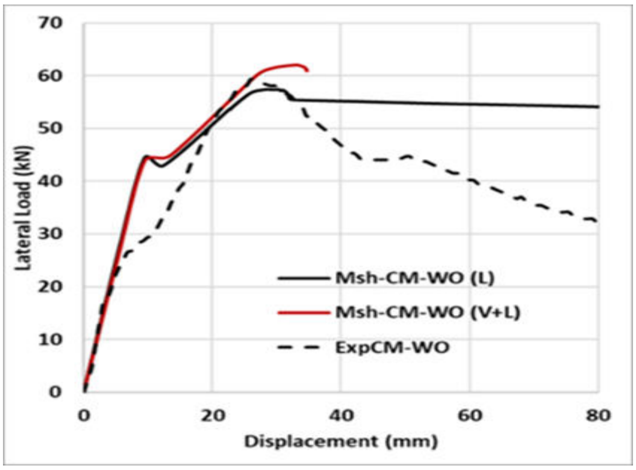

(b)

Figure-9. (a) CM-WO subjected to both vertical and lateral loading and (b) the load-displacement curves of Msh-CM-WO (L) and Msh-CM-WO (V+L).

The comparison of stress contours between the model validated with lateral loading only and the model validated with a combination of vertical and lateral loading shows an increase in compressive stress on the wall after adding vertical loading. The compressive stress on the wall increases from 1,077 MPa to 1,213 MPa. On the other hand, the tensile stress decreases from 0,486 MPa to 0,375 MPa, and the shear stress also decreases from 0,537 MPa to 0,492 MPa. The maximum compressive stress at the bottom end of the column also increases to 6,356 MPa. Additionally, there is a decrease in the tensile stress of the steel confinement to 413 MPa. All of these results indicate that the addition of vertical loading causes compressive forces on the wall.

3.4 Equivalent Frame and Rigid Zone in MSC

The CM-WO uses confining elements in the form of tie columns and tie beams made of reinforced concrete. These elements serve to tie the masonry units together and are capable of resisting both gravity and lateral loads. The tie columns and beams are not modeled as composite sections in the ordinary diagonal strut model. Figure-10 (a) shows the deformation of the ordinary diagonal strut

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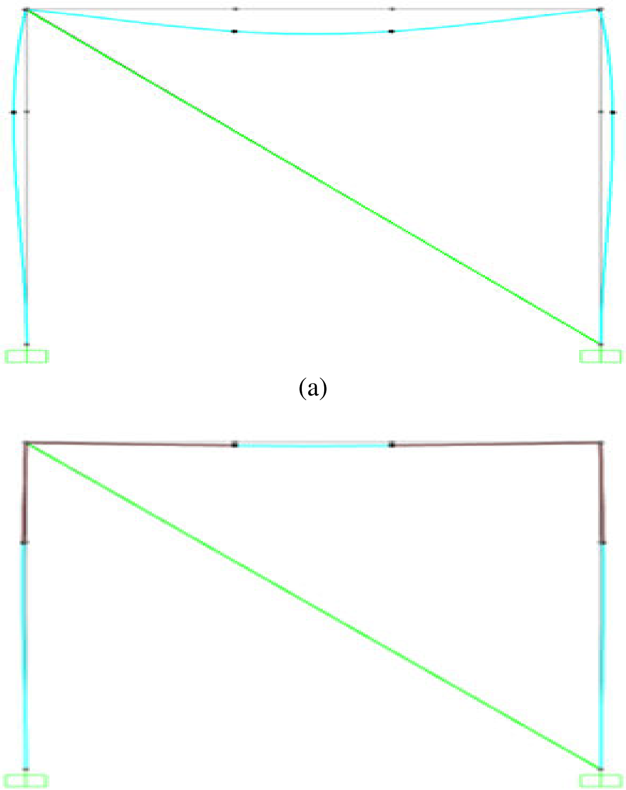
model subjected to a combination of vertical and lateral loads (V+L). On the other hand, in the MSC-WO (V+L) model shown in the Figure-10 (b), the tie columns and tie beams experience an increase in stiffness, assuming the tie columns are rigid and composite with the masonry wall through confining elements.



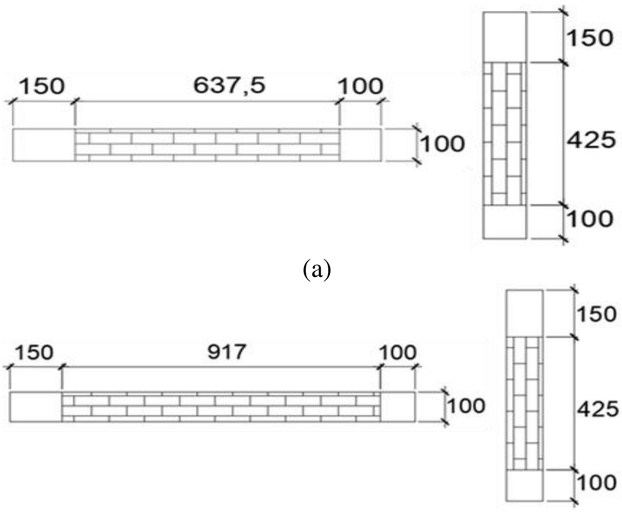
(a)

(b)

Figure-10. The deformation pattern is due to the combined vertical and lateral load (V+L) (a - Top) ordinary diagonal strut and (b - Bottom MSC).

The research results indicate that the maximum deflection in the tie beam is enormous in the ordinary diagonal strut model, resembling an open frame model, which does not match the behavior of the shell model showing small beam deflections. The diagonal strut also does not support the beams and columns, resulting in significant vertical deformations in the tie beams. This behavior is inconsistent with the behavior of CM, which should act as a composite structure with its confining elements.

In reality, the tie beams in CM are continuously supported by the walls, resulting in minimal vertical deflections of the beams when subjected to gravity loads. The columns also behave as a composite with the walls, experiencing no bending. Therefore, the strut model must be combined with the rigid zone factor and composite confining elements. The composite beam and column were calculated based on geometry. For example, the dimensions of the composite cross-section for beams and columns of MSC-CWO20 and MSC-CDO20 can be seen in Figure-11 (a) and (b). A rigid Zone Factor of 100 was used for all models. The confining elements in the MSC model (combination strut) exhibit behavior consistent with CM, acting as a composite with the walls and demonstrating deflections in line with CM principles.



(a)

(b)

Figure-11. Composite cross-section for beams and columns (a) MSC-CWO20 and (b) MSC-CDO20.

3.5 Msh Model with Centric and Eccentric Openings

At this stage, there are three opening positions on the wall, namely CM with centric openings (C), CM with eccentric openings near lateral loading (Near Load/NL), and CM with eccentric openings far from lateral loading (Far Load/FL). The samples used to investigate the effect of location and type of openings are CM with door and window openings with a 20% opening ratio.

Based on the load-displacement curve of the Msh-CWO20 model, as seen in Figure-12 (a), the influence of eccentricity on window openings is minimal when viewed from the stiffness and maximum load-carrying capacity, which are almost the same. Therefore, different opening locations can be treated equally to simplify the MSC for window openings.

On the other hand, based on the load-displacement curve of the Msh-CDO20 model, as seen in Figure-12 (b), the influence of eccentricity on door openings is quite significant, as seen from the difference in stiffness and maximum load-carrying capacity. Therefore, for CM analysis with door openings, the MSC model is created based on the location of the door openings and has three different types.

The Load-Displacement graph shows that walls with door openings are slightly more robust compared to walls with window openings. However, the stiffness of walls with window openings is better than those with door openings in the middle and those with door openings far from lateral loads. Therefore, for analysis and design of CM, door and window openings cannot be treated the same.

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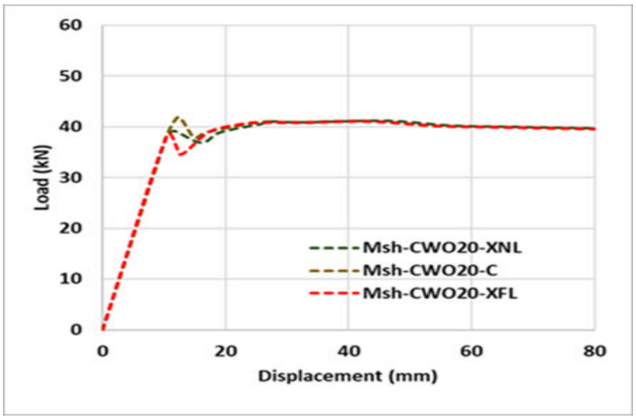

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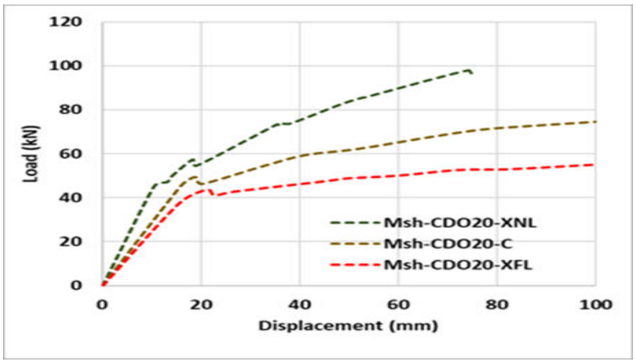


(b)

Figure-12. Load-displacement curve of the (a) Msh-CWO20 and (b) Msh-CDO20.

3.6 Comparison of MSC and Msh

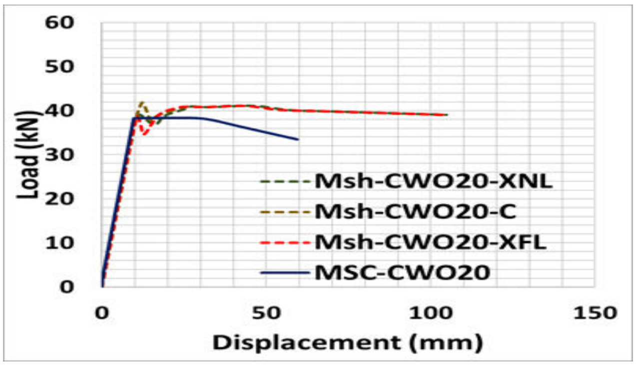
The results of modeling Msh with different types and opening positions are used as a reference in creating the MSC model configuration. MSC configuration for CM with window openings is standardized for centric and eccentric openings. Meanwhile, the MSC configuration for CM with door openings needs to have three models according to the location of the openings, namely MSC-CDO20-C, MSC-CD20-XNL, and MSC-CDO20-XFL.

After modifications to the MSC-CWO20 diagonal strut, it was found that a 152 mm x 100 mm strut cross-section could achieve a stiffness similar to the Msh model. However, in the linear graph, the load continues to increase beyond the maximum load of the Msh model. On the other hand, an 80 mm x 100 mm strut cross-section is sufficient to obtain the maximum load, but it has yet to be achieved in terms of stiffness. To get the stiffness required, modifications were made to the axial area factor (AAX) by 1,9 in the MSC-CWO20 model with an 80 mm x 100 mm strut cross-section. The modified result shows that the MSC-CWO20 model now has the appropriate stiffness and strength, similar to the Msh model. The V-d curves of the Msh-CWO20 and MSC-CWO20 models are shown in Figure-13 (a). With these modifications, the MSC-CWO20 model can achieve a response similar to the Msh model without exceeding the maximum load and maintaining its stiffness.

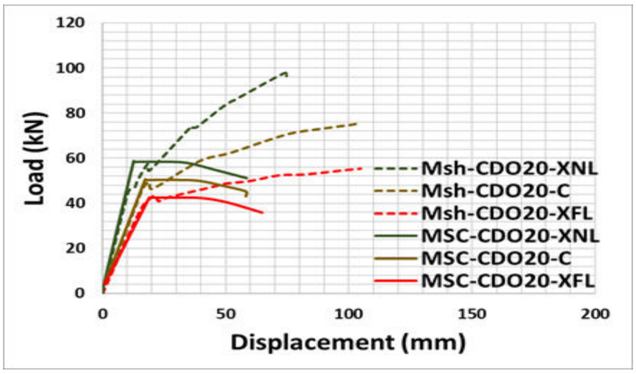
The diagonal strut MSC-CDO20 was modified using the same method applied to MSC-CWO20. The results of the modifications are as follows:

- The cross-section of the MSC-CDO20-C strut is 115 mm x 100 mm with an axial area factor (AAX) of 1,45. This modification was made to achieve the appropriate stiffness similar to the Msh-CDO20 model.
- The cross-section of the MSC-CDO20-XNL strut is 130 mm x 100 mm with an axial area factor (AAX) of 1,45. The MSC-CDO20-XNL model can achieve a response similar to the Msh-CDO20 model through this modification.
- The cross-section of the MSC-CDO20-XFL strut is 100 mm x 100 mm with an axial area factor (AAX) of 1,45. This modification ensured that the MSC-CDO20-XFL model had the appropriate stiffness, similar to the Msh-CDO20 model.

By using the same method as in MSC-CWO20, the modifications to the diagonal strut MSC-CDO20 allow the MSC-CDO20-C, MSC-CDO20-XNL, and MSC-CDO20-XFL models to achieve the appropriate response similar to the Msh-CDO20 model while maintaining their stiffness. The load-displacement curves of these three models are shown in Figure-13 (b). The load-displacement curves generated from these three models show results consistent with the Msh-CDO20 model.



(a)



(b)

Figure-13. Load-displacement curves (a) Msh-CWO20 and (b) Msh-CDO20.

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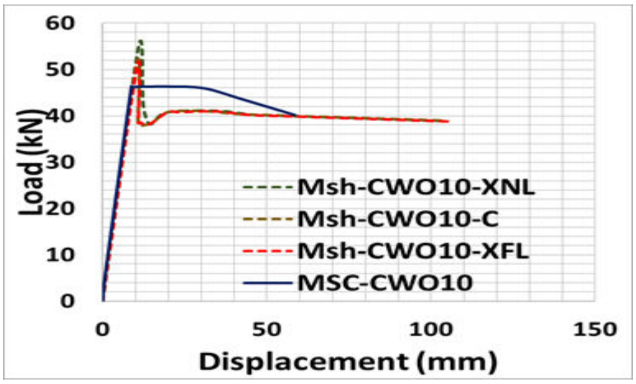
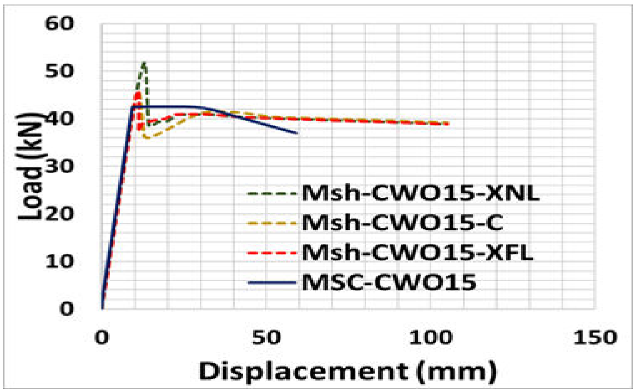
3.7 MSC with Various Opening Ratios

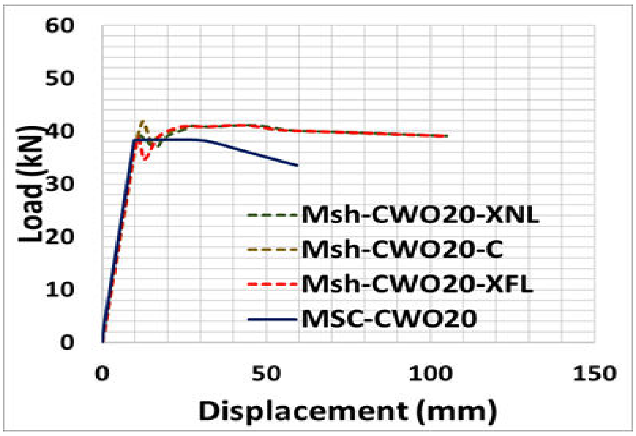
MSC with different opening ratios (r) is created using Msh-CWO20 and Msh-CDO20 as a reference. The cross-sectional size of MSC struts and its axial area factor are modified to replicate the response of Msh. Confined Masonry (CM) variations with window openings are made with opening ratios of 10%, 15%, 20%, 25%, and 30%, while CM with door openings is made with opening ratios of 20%, 25%, and 30%. The load-displacement curves of the Msh and MSC models are then plotted on the same graph as shown in Figure-14.



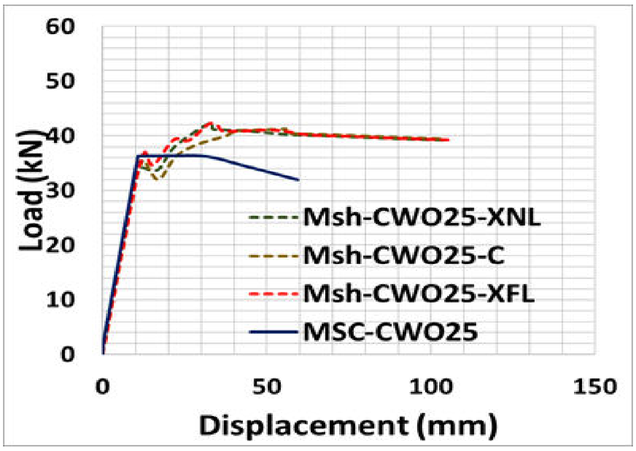
(a)



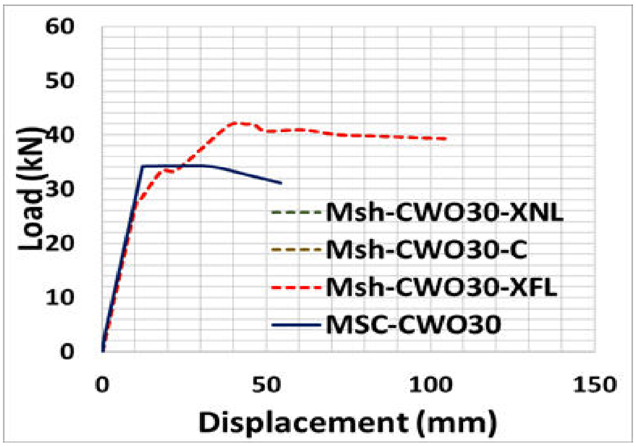
(b)



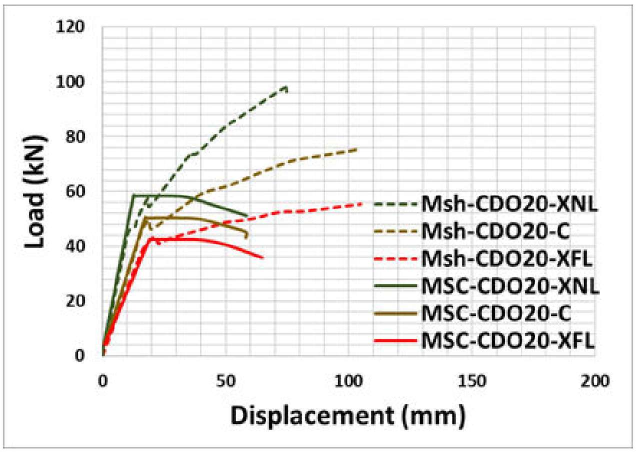
(c)



(d)



(e)



(f)

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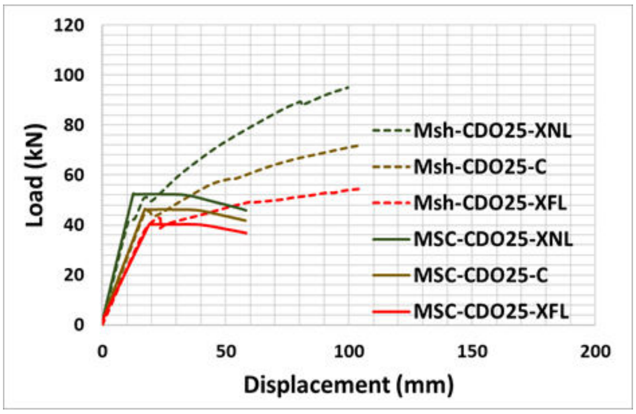
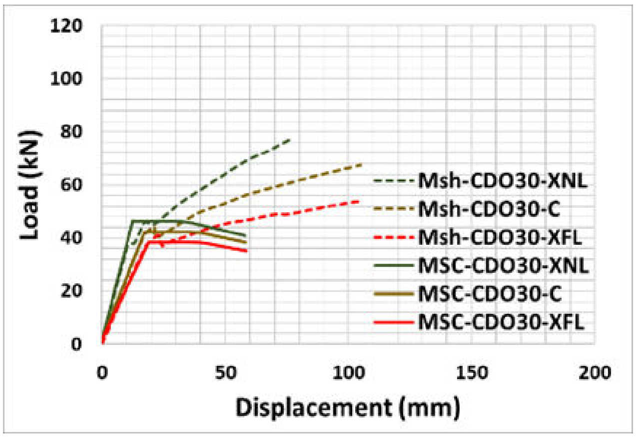


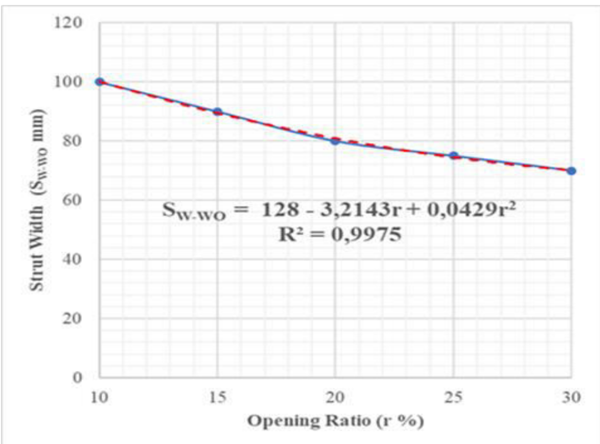
(g)



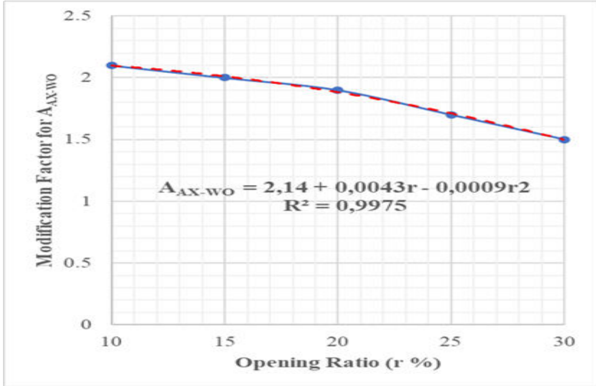
(h)

Figure-14. The load-displacement curves of the Msh and MSC of the CM with various opening ratios: (a) CWO10, (b) CWO15, (c) CWO20, (d) CWO25, (e) CWO30, (f) CDO20, (g) CDO25, and (h) CDO30.

The relationship between the opening ratio (Or in %) and the Strut Width ($S_{W\text{-}WO}$ in mm) is plotted in Figure 15. (a), and/or with the axial area factor of MSC for window openings ($A_{AX\text{-}WO}$) plotted in Figure-15. (b).



(a)



(b)

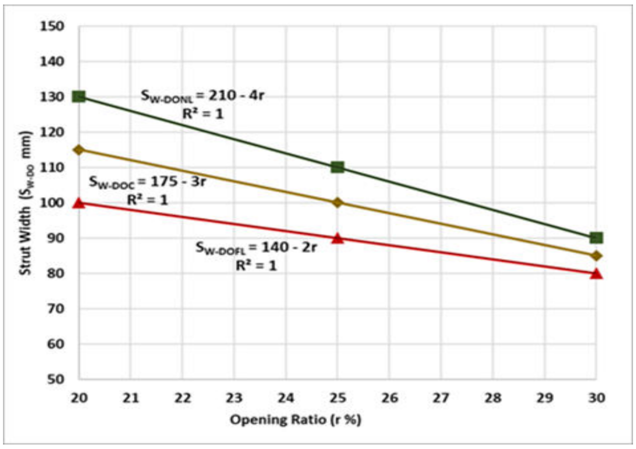
Figure-15. The relationship between the window opening ratio (Or in %) (a) With Strut Width and (b) With Axial Area Factor of MSC.

Based on the relationships in the graphs above, CM with window openings can be represented by equations (4) and (5).

$$S_{W-WO} = 128 - 3{,}2143r + 0{,}0429r^2 \quad (4)$$

$$A_{AX-WO} = 2{,}14 - 0{,}0043r - 0{,}0009r^2 \quad (5)$$

The relationship between the opening ratio (Or in %) and the Strut Width ($S_{W\text{-}DO}$ in mm) is plotted in Figure-16. (a), and/or with the axial area factor of MSC for door openings ($A_{AX\text{-}DO}$) plotted in Figure-16. (b).



(a)

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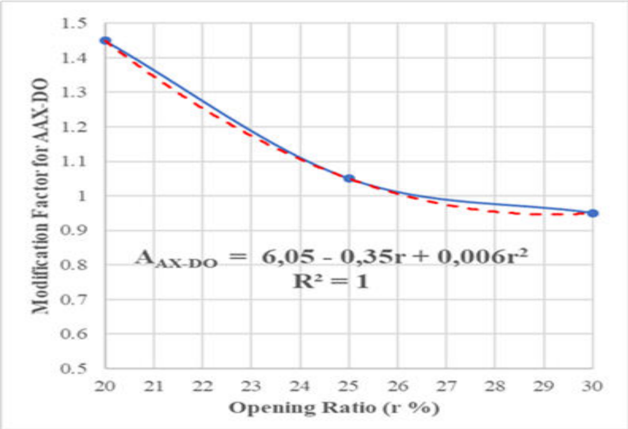

(b)

Figure-16. The relationship between the door opening ratio (Or in %) (a) with Strut Width and (b) with the Axial Area Factor of MSC.

Based on the relationship shown in the graph above, the CM with door openings yields the following equations: (6), (7), (8), and (9).

$$S_{W-DONL} = 210 - 4r \quad (6)$$

$$S_{W-DOC} = 175 - 3r \quad (7)$$

$$S_{W-DOFL} = 140 - 2r \quad (8)$$

$$A_{AX-DO} = 6{,}05 - 0{,}35r + 0{,}006r^2 \quad (9)$$

4. CONCLUSIONS

The research on CM structures with openings, reinforced around the openings, and subjected to vertical and lateral loads have been successfully analyzed using a combination of diagonal struts with equivalent frames and rigid zones (MSC). The study also involved validation models using layered shells (Msh), which were then developed for various opening ratios of 10% to 30% and both centered and eccentric positions of the window and door openings. The following are the conclusions drawn from the research findings:

a) The layered shell model (Msh) effectively depicts the behavior of CM structures with openings by reducing the elastic modulus of concrete and masonry materials using a reduction factor of 0,1.
b) The combination strut method (MSC) using 100 times rigidness factors for beams and columns and varying axial area factors (Aax) yields responses that match the Msh responses for CM structures with openings.
c) Diagonal struts can be modeled concurrently using the tension limit feature to resist lateral loads from two opposing directions.
d) CM structures with window openings (CWO) and door openings (CDO) with the same opening ratios exhibit different responses. Hence, the width of struts for these two types of CM differs as well.
e) The equations for the width of struts and the Aax factor for CM structures with centered and eccentric window openings are described by equations (4) and (5). However, a distinction between centric and eccentric cases for CM structures with door openings is needed, as shown in equations (6) to (9).

ACKNOWLEDGEMENTS

The Udayana University of Bali partially funded the study through a funding grant of PUU no B/1.784/UN14.4.A/PT.01.03/2023.

REFERENCES

[1] S. Brzev, R. Meli. 2012. International Guideline for Seismic Design of Low-Rise Confined Masonry Buildings in Regions of High Seismic Risk, 15th World Conference on Earthquake Engineering (15WCEE).

[2] M. Sukrawa, I. A. M. Budiwati. 2019. Analysis and Design Methods for Infilled Frames with Confined Openings. International Journal of Technology. 10(5).

[3] R. Meli, F. Crisafulli, A. J. Dai, C. M. Farsi, A. T. Hart, A. Mebarki, F. A. S. Moghadam, D. Quiun, M. Tomazevic, S. L. Yamin. 2011. Seismic Design Guide for Low-RIse Confined Masonry Buildings Prepared by Confined Masonry Network a Project of the World Housing Encyclopedia, EERI & IAEE with funding support from Risk Management Solutions Seismic Design Guide for Low-Rise Confined Masonry Buildings 2 Acknowledgments, Oakland, California.

[4] B. Borah, V. Singhal, H. B. Kaushik. 2021. Assessment of Seismic Design Provisions for Confined Masonry Using Experimental and Numerical Approaches. Engineering Structures. Vol. 245.

[5] 2018. EERI, Promoting the Use of Confined Masonry Construction, EERI Policy Statement, Oakland, California.

[6] K. V. Ghaisas, D. Basu, S. Brzev, J. J. Pérez Gavilán. 2017. Strut-and-Tie Model for Seismic Design of Confined Masonry Buildings, Construction and Building Materials. Vol. 147.

[7] B. Borah, V. Singhal, H. Kaushik. 2021. Assessment of Important Parameters for Seismic Analysis and Design of Confined Masonry Buildings: A Review. Advances in Structural Technologies.

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

[8] K. Rangwani, S. Brzev. 2016. Seismic Analysis of Confined Masonry Shear Walls Using the Wide Column Model. Applied Mechanics and Materials. Vol. 857.

[9] B. Borah, H. B. Kaushik, V. Singhal. 2021. Development of a Novel V-D Strut Model for Seismic Analysis of Confined Masonry Buildings. Journal of Structural Engineering. 147(3).

[10] M. M. Ajmal, A. U. Qazi, A. Ahmed, U. A. Mughal, S. Abbas, S. M. S. Kazmi, M. J. Munir. 2023. Structural Performance of Energy Efficient Geopolymer Concrete Confined Masonry: An Approach towards Decarbonization, Energies. 16(8).

[11] M. Sukrawa, I. G. P. I. M. Putra, I. A. M. Budiwati, IPB. Bhisama. 2022. Strut Method for the Analysis of Confined Masonry Structure with Opening. 5th International Conference on Earthquake Engineering and Disaster Mitigation.

[12] M. Suarjana, D. Kusumastuti, K. S. Pribadi, A. Rildova. 2012. An Experimental Study on the Effect of Opening on Confined Masonry Wall under Cyclic Lateral Loading. 15th World Conference on Earthquake Engineering.

[13] P. Agrawal, M. Shrikhande. 2006. Earthquake Resistant Design of Structures, PHI Learning Pvt. Ltd, New Delhi.

[14] 1996. European Committee of Standardization (CEN), Design of Masonry Structures Part 1-1 Eurocode 6: General Rules for Buildings-Reinforced and Unreinforced Masonry. European Committee of Standardization (CEN), UK.

[15] K. Shahzada, S. Profile, K. Khplwak. 2023. Comparison of Confined and Semi-Confined Masonry Structures. International Conference on Recent Advances in Civil Engineering and Disaster Management.

[16] A. S. Arya, T. Boen, Y. Ishiyama. 2013. Guidelines for Earthquake Resistant Non-Engineered Construction. The United Nations Educational Scientific and Cultural Organization (Unesco).