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Strut Method for the Analysis of Confined Masonry Structure with Opening

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Abstract

Confined masonry construction (CM) is an efficient earthquake-resistant structural system that consists of masonry walls as the main structure and RC tie columns and beams as confining elements. Despite the growing application of CM for residential buildings, its analytical method is still inconclusive. Researchers have proposed the Strut and Tie and V-D strut method, but it does not explicitly cover the CM wall with an opening. This study proposed a strut method to analyze CM walls with confined openings. Before developing the strut model, the CM was modeled using a layered shell element and validated using test results by others. The shell model was adjusted to match the load-deformation curve of the test results. The strut models for various centric opening ratios were adjusted to match the stiffness of the valid shell models to obtain the relationship between the opening ratio, strut dimension, and modifying factor for strut axial area. All models were analyzed using static pushover to obtain nonlinear P-d curves of the models without vertical load. The confinement effects on the wall opening and opening types were also investigated. Analysis results show that the responses of shell models with reduced elastic moduli produce responses that mimic the test results well. Strut models with their dimensions and axial area modifying factors were proposed for the analysis to match the validated shell results. The effect of opening confinement significantly increases the stiffness of the wall, but the different opening types of the same ratio slightly change the CM responses. Nevertheless, the confining elements will halt the crack initiated on the corners of the opening.

Keywords

Confined masonry structure, Diagonal strut model, Layered shell, Seismic resistant building, Wall with confined opening

1. Introduction

Confined masonry (CM) is a construction technique and a conventional building method. It comprises a masonry wall as the main component and reinforced concrete (RC) tie column and tie beam as confining elements. Combining both elements produces strong, stiff, ductile composite structures suitable for residential buildings in seismically active areas. The flexible-but-ductile RC elements confine the brittle-but-rigid masonry wall, making the wall stronger and stiffer. In the CM, walls are constructed first and later confined with reinforced concrete at surrounding edges.

The CM constructions are widely used for residential buildings worldwide, including those built in seismically active regions, that could enhance seismic resilience even by utilizing widely available materials. In Indonesia, however, CM construction is used mainly for simple, non-storied houses. In contrast, CM is used for low-rise residential buildings in other parts of the world and has had great success. CM can be an affordable seismic-resistant construction technology because this practice does not require new or advanced construction materials, skills, tools, or equipment [Borah et al., 2019]. Research has shown that CM construction is much stiffer and stronger than other masonry constructions, such as unreinforced and reinforced masonry [Chourasia et al., 2016].

Indonesia, as a seismically active region, does not have building codes for CM construction, and as a result, very rarely were double or multi-story residential buildings built using this type of construction. In other seismic regions such as Mexico, Chili, China, and India, CM is used for multi-story buildings and has survived many strong earthquakes [Meli et al., 2011]. In India, extensive scale applications of CM for dormitory buildings at the IITGN campus were reported [Jain et al., 2011]. As many as 6 of 3-story and 30 of 4-story buildings were built using CM construction. The project is among the first in the country and is expected to be efficient and safe to withstand the 7.7 Richter earthquake that shook the region in the past.

Due to CM's affordability as a resistant construction technique, the Earthquake Engineering Research Institute (EERI)` in California issued a policy to promote CM technology use for four-storied or lower residential buildings [EERI, 2018]. Accordingly, many construction guidelines were produced to encourage the proper application of the techniques. Despite the wide application and extensive promotion of CM construction in seismic regions, the analytical method for this type of structure has still not been developed. The CM construction design guide is more practical than theoretical. The suggested practical guidelines to design CM construction are: adequate wall density index, regular and symmetrical plan, proper confining elements and reinforcement detailing, good quality masonry, good interface between the wall and confining elements, a small aspect ratio of wall panel, opening location, and opening size.

Opening on walls of residential buildings is an absolute necessity, and cracks in the corners of wall openings are a typical scene. Accordingly, a CM wall with an opening and reinforcement around the opening is one important aspect of CM construction that needs to be considered in the design. Few researchers suggest analytical methods for CM walls, but it does not cover specific cases such as CM walls with confined openings, so it become an important research topic. The complexity of the behavior of the CM wall under seismic loading is another issue that needs to be solved.

Ghaisas et al. (2017) proposed a Strut and Tie Model of CM to model laterally loaded CM structures. Both strut and tie are non-dimensional, and no evidence has been shown to show whether the model is accurate. Another strut method was proposed by Borah et al. [Borah et al., 2021] with great detail. They claimed that, with a strut width of one-third the diagonal length, the method could mimic the load-deformation curve of tested CM quite well, provided that the elastic modulus of the tie beam is enlarged by a factor of 20. This theory is interesting to evaluate because the strength depends on the strut buckling load when dealing with a diagonal strut. Therefore, the critical buckling load of the strut is of concern.

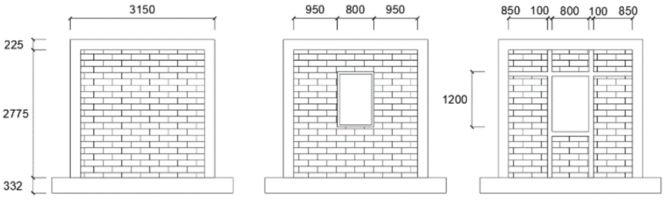
Modeling of CM walls is computationally complex and requires some input parameters that are not readily available. No guidelines are available regarding the analysis of CM walls under combined vertical and lateral loads. This research aims to obtain a preliminary strut model for analyzing CM walls with confined openings of various sizes, after which laboratory tests can be done. Confinement of the wall opening is important because, almost always, the crack in the wall with the opening starts from the corner of the opening. In addition, from test results of the infilled frame with a confined opening reported by Sigmund and Penava [Sigmund and Penava, 2014], it was shown that the strength and stiffness of an infilled frame with the confined opening are nearly the same as that of an infill frame with solid infill wall. The available test data was limited for the CM wall with confined openings. Accordingly, shell element models were created to compare before developing the strut model. The strut model proposed in this paper is strictly limited to the case of laterally loaded CM walls with centric confined openings.

2. Materials and Methods

There are many ways of modeling a CM wall: using 3D elements such as solid or brick elements, 2D elements such as shell elements, and 1D elements such as frame elements. The compressive strut method is the most commonly suggested method for analyzing CM structures. The method considers only the wall under compression, while part of the wall under tension is assumed to be cracked and excluded from the analysis. In this study, the diagonal strut method was developed and used to model the load-deformation curve of the CM wall with a confined opening. Due to the limited available test data on the CM wall with a confined opening, the shell element model (MSh) was created before the strut model (MSt) was developed. Therefore, the proposed strut model can be compared to the shell element model.

2.1 Validating Shell and Strut Models

This study began with CM modeling using shell elements to be validated with test results by Suarjana et al. [Suarjana et al., 2012]. Only lateral load is considered in this study, following the test setup. Two models were created: the first model is for CM with a solid wall (MSh-Solid), and the second one is for CM wall with window opening (MSh-WO) with size and dimensions according to the test data [Suarjana et al., 2012] as shown in Figure 1(a) and 1(b). Included in Fig. 1(c) is an example of a wall with confined openings with extended columns (WOCec) considered in this research.



(a) (b) (c)

Fig.1 Dimension in mm of Tested Models: (a) CM-Solid, (b) CM-WO, and (c) Model of CM Wall with Confined Opening CM-WOCec

As shown in Fig. 1, the tested CM with a 100 mm thick brick wall was confined with a tie column and tie beam of 100 by 225 mm. Fig. 1 ((a) and (b)) shows CM with a solid wall (CM-Solid) and CM with a window opening (CM-WO) of opening size 800 by 1200 mm, which corresponds to a 13% opening ratio. A 50 by 100 mm wooden window frame was used around the opening. The confining element was reinforced with four rebars of 10 mm and 8 mm stirrups. Seismic detailing of beam-column joints was provided following the guidelines for seismic-resistant houses from the Ministry of Public Work of Indonesia [PUPR, 2009]. The properties of materials used are 2.32 MPa for wall, 18 MPa for concrete with a yield strength (fy) of 385 MPa, and 350 MPa for longitudinal and transversal rebar, respectively. The other properties, such as elastic modulus and Poisson ratio, were not reported in the test report [Suarjana et al., 2012], and accordingly, values were assigned from references. The elastic modulus of masonry and concrete were calculated using equations 1 and 2 from Agarwal and Shrikhande [Agarwal and Shrikhande, 2009]. The value for Em was 1740 MPa, and Ec was 18396 MPa.

$$E_m = 750 f_m \quad (1)$$

$$E_c = 4700\sqrt{fc} \quad (2)$$

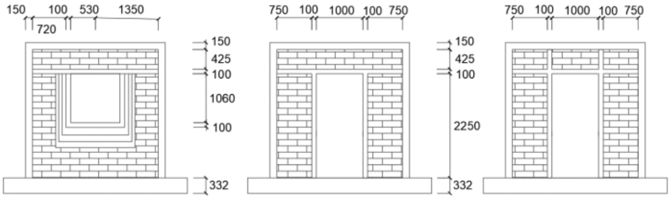
The layered-shell element was used to model all components of the CM wall, a unique feature of shell element in SAP 2000 software to model the nonlinear behavior of concrete [CSI, 2013]. The validity of the shell model is determined from the similarity of force-deformation (P-d) curves obtained from the models and the test results. The values of some properties inputted in the software for solid models were modified so that the obtained curves matched those of the test results. This step was done because it is generally accepted that shell element models tend to be stiffer than the actual model. Furthermore, distorted shell element models were created only as a reference to develop a strut model for CM walls with a confined opening because there is no adequate test data available. Observing stresses developed in layered shells was also used to validate shell models.

Strut models for the tested CM wall were also created to match the results from shell models and the test results. The strut's dimension and axial cross-sectional area (A_{ax}) were determined by trial to match the P-d curves from the test results. After the validation of strut models for the tested CM wall, a new model of CM with a confined opening (shown in Fig. 1(c) was created to study the effect of confinement on the models' response.

2.2 Validating Shell and Creation of Strut Models for CM wall with Confined Openings

The strut models for CM walls with confined openings are created for various opening ratios. Modifying tie columns and tie beam sizes followed the guidelines for simple housing [PUPR, 2009]. The tie column and beam were 150 by 150 mm, and the wall thickness was 100 mm. At the same time, the corresponding shell models of the CM wall are also made using the same distortion technique applied to the valid MSh. The similarity of P-d curves of the strut model and shell model was used to determine the validity of the strut models.

A lintel beam or bond beam of 100 by 100 mm was used above the opening across the wall panel to match the wall thickness. The bond beam was suggested by EERI [EERI, 2011] to strengthen the opening and reduce the wall aspect ratio. Tie column and beam were used around the opening, considering the advantages of confining the opening in an infilled frame [Sigmund and Penava, 2014]. The opening percentage on the wall was 13, 15, 20, 25, and 30%. Only centric opening is considered in this paper. Figure 2 shows the CM wall with the confined opening of various opening ratios (Fig. 2(a)), confined door opening (Fig. 2(b)), and confined door opening with extended columns (Fig. 2(c)).

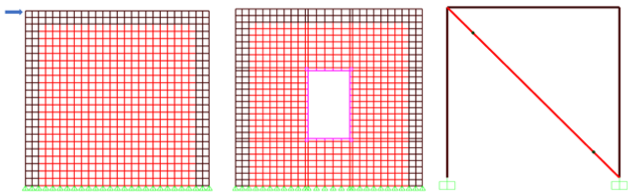


(a) (b) (c)

Fig. 2 Dimension in mm of CM Wall with Confined Opening: (a) CMWOC of Various Opening Ratios, (b) CM-DOC, and (c) CM-DOCec

An additional model with the window and door opening of 30% was created to study the effect of opening type (window and door opening of the same ratio). Both openings are centric, as shown in Fig. 2.

In the layered shell model, the masonry wall was assumed to be homogenous. Therefore, no attempt was made to model the individual brick. For the confining elements composed of concrete and reinforcement, the layered shell method enables more precise modeling. The confining elements are represented using shell elements consisting of concrete layers and reinforcement layers, where the thickness of each layer is adjusted according to the dimensions of the concrete and the amount of reinforcement used in the test specimen. The position of the reinforcement can also be explicitly modeled within each layer, following the layered shell modeling procedure in the SAP2000 software [CSI, 2013]. By specifying the thickness and material properties for each layer, the stress distribution between concrete and steel can be analyzed with greater accuracy, thereby enhancing the understanding of composite structural behavior under loading. Additionally, the interface between the foundation and the wall was modeled as pin support. Figure 3 shows the models for the tested solid CM walls, MSh-Solid (Fig. 3(a)), MSh-WO (Fig. 3(b)), and the strut models, MSt (Fig. 3(c)). The tie column and beam were modeled as frame elements. The wall was modeled as a frame element with both ends released against rotation.



(a) (b) (c)

Fig. 3 Shell and Strut Models for the Tested CM Wall

All models were analyzed with nonlinear static pushover analysis, a displacement-controlled feature in SAP2000 [CSI, 2013], using an input displacement target of 3.5 percent or equivalent to 105 mm. The diagonal strut was assigned P-M hinges at its middle length. The pushover results from the analysis are the lateral load-deformation (P-d) curves showing the model stiffness and load-carrying capacity.

3. Results and Discussion

3.1 Nonlinear layered shell

The final result of the validation models is presented in Fig. 4 in the form of lateral load and displacement (P-d) curves. Blue lines represent the solid CM wall (CM-Solid), and red lines represent the wall with a window opening (CM-WO). During the trial of validating shell models against test results (shown in dashed lines), it was found that the shell models of CM wall (MSh – dotted lines) were only slightly stronger than the tested CM walls. However, the models were much stiffer than the tested CM. The models were then adjusted by reducing the elastic moduli of the masonry wall and the confining concrete to fit better the tested CM's stiffness. The adjusted shell models were named DistMSh (solid lines). It turned out that by reducing the elastic moduli of concrete and masonry walls by a factor of 0.1, the DistMSh can fit the lower part of the P-d curves of the tested CM. These results are consistent with the findings reported in the previous study by Sukrawa et al., (2024). The upper parts of the curves (post-crack) of the models still deviate from the test results, meaning that shell models could not ideally mimic the post-crack responses of the tested

CM walls. However, the model's response can be considered adequate for the analysis and design of the CM wall because, in seismic design, the design lateral loads are generally much lower than the structure's capacity. The elastic moduli reduction can be associated with lower actual strength, cracked elements, or other reasons. Nevertheless, these distorted shell models are then used as a reference to develop diagonal strut models (MSt). Figure 5 shows the P-d curves of CM modeled using struts.

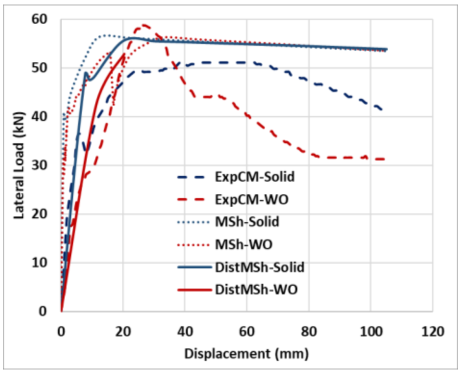


Fig. 4 P-d Curve of Tested CM Walls under Lateral Load (Distorted Shell Models)

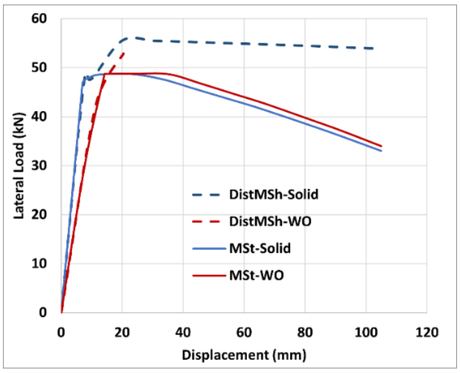


Fig. 5 P-d Curve of Tested CM Walls under Lateral Load (Strut Models)

The P-d curves of the strut models for solid and opened CM walls are presented in Fig. 5, together with the corresponding shell models DistMSh. The strut dimension for the tested models that matched the P-d curve of the shell model was 100 x 100 mm. However, its cross-sectional axial area (A_{ax}) was modified to match the stiffness of the tested CM. By trial, a modification factor (FA_{ax}) of 2.7 for MSt-Solid and 1.3 for MSt-WO produced responses that closely match the stiffness of shell models and, therefore, match the stiffness of the tested CM walls.

It is apparent from Fig. 5 that the shell and strut models match the test results of the CM wall after some modification. For the shell models, a reduction of elastic moduli is necessary to match the stiffness of the tested wall. However, the maximum lateral load still slightly exceeds the test data. The elastic moduli of the material do not need to be modified for the strut models. To match the responses of shell models and the tested wall, a strut dimension of 100 by 100 mm is enough to obtain maximum lateral load, but its axial area (A_{ax}) needs to be enlarged to match the stiffness.

The stresses in the models for the tested CM wall with opening were observed, and the summary of the stresses is given in Table 1. The shear strength of the masonry wall of 2.32 MPa is 0.39 MPa. Therefore, the shear stresses at the corners of the opening already exceed their limiting value. The following test results show that all corners of the opening were reported cracked.

Table 1. Stresses on the CM Models

Material	Normal Stress (MPa)	Location	Shear Stress (MPa)	Location
Masonry	1.7	Bottom of wall	0.52	Corner of opening
Concrete	14	Bottom of column		
Steel	450	Bottom of column		

3.2 Confinement Effect

Additional models were created based on the tested model of CMWO13 to investigate the effect of confinement on wall opening. The responses of the strut models for a small opening ratio (13%) are presented in Fig. 6. The MSt-WO13 (solid red line) used a 100 by 100 mm strut with an FA_{ax} of 1.3. For the MSt-WOC13, the exact strut size was used with an FA_{ax} of 10. For the Mst-WOCec13, the strut size was 100 by 150 mm with an FA_{ax} of 8.

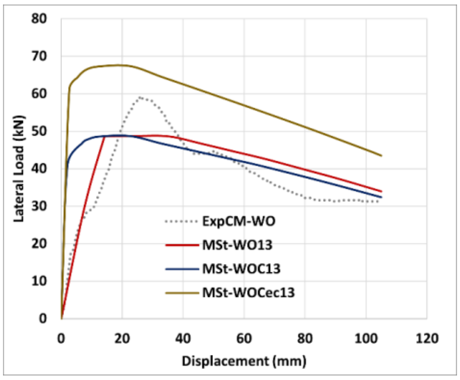


Fig. 6 CM Models with Confined Window and Door Opening. (Model with 13% DOC and DOCec)

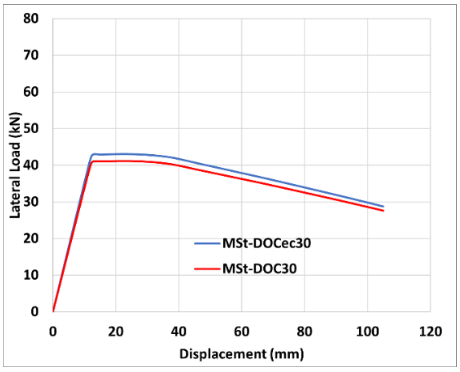


Fig. 7 CM Models with Confined Window and Door Opening (Model with 30% DOC and DOCec)

From Fig. 6, it can be seen that the confinement of the wall opening dramatically increases the stiffness of CM walls without increasing its maximum load-carrying capacity, as shown by MSt-WO and MSt-WOC. Confinement of opening using an extended column, however (MSh-WOCec), significantly increases the CM walls' stiffness and load-carrying capacity. Figure 7 also shows the extended column's effect on the CM wall's load-carrying capacity with a 30% door opening. Comparing the two figures, it is apparent that the stiffness and strength increase due to the extended tie column being more pronounced in the CM wall with a smaller opening ratio.

3.3 Creation of Strut Models for CM with Confined Opening of Various Ratios

The strut models of CM wall with confined openings of various opening ratios (OR) were created using the distorted shell models as reference. Two confining elements were considered, one without an extended column (WOC) and the other with an extended column (WOCec), as shown in Figs. 2(a) and 2(b). Both types were provided with a bond beam of 100 by 100 mm. The materials used have the same properties as those used in the tested CM walls.

Only confinement with non-extended columns was considered to obtain the relationship between OR and the strut properties. For the shell models, the same concept was used, that the elastic moduli of the materials were reduced by a factor of 0.10. Figure 8 shows the P-d curves of strut models associated with the shell models plotted in dotted lines of the same color. The response of strut models was adjusted by varying the strut dimension and its axial area to match the stiffness of shell models but with a slightly lower maximum load to have the lower bound model. It is apparent from the figure that the smaller the opening ratio, the stiffer and the stronger the models become.

The relationship between the opening ratio (OR in %), the strut dimension (SA), and the modifying factor for A_{ax} (FA_{ax}) is shown in Table 2. The relationship was also plotted in Fig. 9 with trend lines. The relations are given in equations (3) and (4)

$$SA = -50\,OR + 850 \quad (3)$$
$$FA_{ax} = -0.24\,OR + 2.45 \quad (4)$$

Note that the strut area is the direct multiplication of strut dimensions. However, the thickness of the strut should be the wall thickness. Accordingly, the other dimension must be calculated to have the same area, corresponding to the opening ratio.

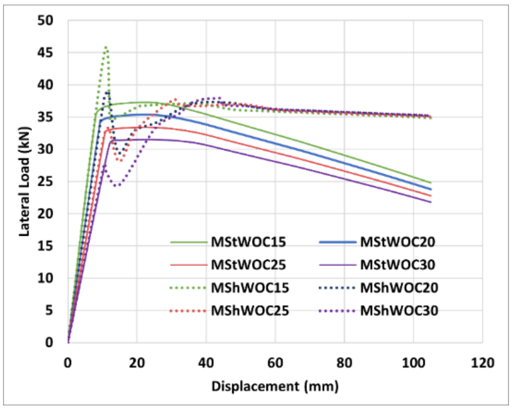


Fig. 8 Responses to CM Wall of Various Opening Percentages. Shell Models (Dotted Lines) and Strut Models (Solid Lines).

Table 2. Relationship Between Opening Ratio and Modification Factor for Aax

OR (%)	Strut Dimensions (mm)	FA_{ax}
15	100 x 80	2.2
20	100 x 75	2.0
25	100 x 70	1.7
30	100 x 65	1.5

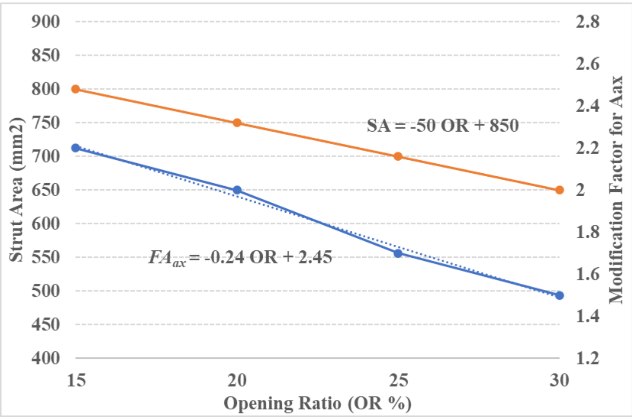


Fig. 9 Relationship Between Opening Ratio, Strut Area SA, and Modification Factor FA_{ax}

3.4 Creation of Strut Models for CM with Confined Opening of Various Ratios

Figure 10 shows the P-d curve of the CM wall with door and window opening of 30% ratio: MSt-DOC30 and MSt-WOC30. The wall with the door opening is slightly stiffer and stronger than the window opening. However, different opening types can be treated the same to simplify the analysis of CM walls and the design method for confined openings.

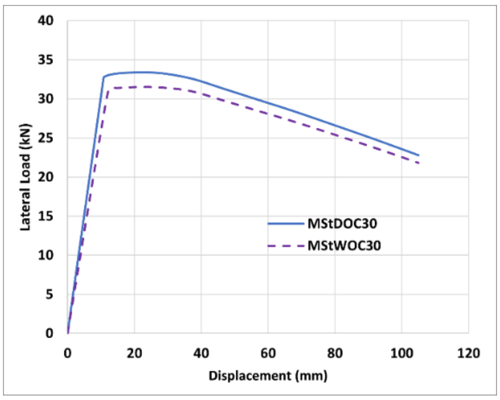


Fig. 10 Responses of CM Wall of strut models with Window Opening (Dotted Lines) and Door Opening (Solid Lines) of the same OR.

4. Conclusion

Referring to the validation models of the tested CM wall, it was found that the responses of shell models with reduced elastic moduli of CM materials produce responses that mimic the test results well. The strut models with an increased axial area of the strut can simulate the responses of the tested CM wall. For analysis and design of the CM wall with a centric confined opening under lateral loading, the strut model can be used with strut dimension and modifying axial area as given in equations (3) and (4).

The effect of opening confinement significantly increases the stiffness of the wall. Furthermore, confinement with extended columns increases the stiffness and strength of the wall, especially when the opening ratio is small. Nevertheless, the door opening is slightly stiffer and stronger than the same opening ratio window opening. However, the difference can be ignored for simplified analysis and design.

Further research is required to analyze the CM wall under combined vertical and lateral loading, followed by experimental testing. In addition, the case of eccentric opening on the wall is another research topic worth investigating.

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