

Modelling of confined masonry structure and its application for the design of multi-story building

Made Sukrawa^{1*}, Gede Pringgana¹, and Putu Ayu Ratih Yustinaputri¹

¹Department of Civil Engineering, Universitas Udayana, Denpasar, Indonesia

Abstract. The confined masonry (CM) structure has been commonly used in the construction of one-story buildings in Indonesia. Its application for multi-story buildings however, is not yet as popular as the alternative options. This research numerically investigated the behavior of confined masonry and its application for use as the main structure of multi-story buildings subjected to seismic loading. From the validation models it was revealed that, using shell element for masonry walls, reinforced concrete beams and tie-columns, the CM model mimic the load deformation curve of tested specimen better than that using frame and shell elements. The application of the modeling technique for the design of 3-story residential building using wall density index less than that suggested in the literature resulted in a safe and stiff structure. The wall stresses under design seismic load were still less than the wall strength and the drift ratio of the model was 0.06% much smaller than the limit of 0.2%. The maximum stress observed at the corners of wall opening justify the need for confinement along the opening.

1 Introduction

The confined masonry (CM) is a building technology that utilizes the masonry wall as the main structure to resist both vertical and lateral loads, while the reinforced concrete beam and tie-column act as confining members. In practice, the masonry walls are constructed first followed by tie-columns and beams [1, 2]. The confining members in CM have some important functions including enhancing the stability and integrity of masonry walls and at the same time, improving the earthquake performance of CM. In a developing country like Indonesia, the CM concept has been widely used for constructing one-story housings, in contrast with the situation in other countries such as India, Peru, and Mexico, where the CM concept has been applied in the construction of multi-story residential buildings [3]. This discrepancy may be caused by the lack of CM-related literature and guidelines that lead to the less confidence of Indonesian civil engineering practitioners regarding the implementation of CM for multi-story residential building. In relation to this circumstance, this paper as part of long-term research on CM is made with aims to contribute to the understanding of CM concept as well as to promote the use of CM in Indonesia as an alternative of less-expensive multi-story building construction method.

*Corresponding author: msukrawa@unud.ac.id

The application of the CM concept to the multi-story residential building requires thicker walls in order to satisfy the wall density index (WDI) requirement. As the wall thickness increasing, the column size that is normally made equal to the wall thickness tends to decrease. Thus, the reduction of column dimension allows the reduction of the demand for reinforced concrete which is more expensive than the masonry wall. The application of CM for a multi-story building, however, should be limited to simple and regular geometry, in which the floor plan and the placement of openings on each floor should be typical [3]. The rule has been made based on the performances of CM building subjected to a strong earthquake in countries like Peru and Mexico. Also, several laboratory experiments have also been reported to study the behavior of the CM under lateral loading.

The methods of modeling the CM structure are not yet widely accepted. Modeling the wall as a shell or brick element is one discrete model while using diagonal compressive strut is a macro model. In case of the use of small size column and beam to confine the wall, the diagonal strut model does not seem appropriate for design, especially when the CM is subjected to vertical load only.

In this paper, a 3-story CM building was designed and modeled using shell element for the wall with a thickness less than that specified in the codes of other countries. Before model the 3-story residential structure, validation models were made by modeling the column and beam as frame element in addition to modeling it as shell element. The responses of the two models were compared to that of the test results by other [4]. The model that mimics the linear part of test result was then applied for the multi-story building structure considering that under seismic design load, the structure is expected to behave linearly and requirements for stiffness and strength are satisfied.

2 Methods

The design of 3-story CM building was done by first selecting a plan of rental houses to be constructed in Denpasar - Indonesia for the site category D. The wall thickness was determined by trial and compared to the requirement of WDI in building codes in another country. As recommended by [3], the WDI value is determined by:

$$\frac{\text{sectional area of the wall}}{\text{total floor area}} \times 100\% \quad (1)$$

The WDI is calculated separately between the transverse and longitudinal walls. The Mexican Regulation also has its guidelines for calculating WDI. The WDI for a 3-story building based on [5] is 3.45%, while according to the Indian code in [3] the WDI value for a 3-story building is 3%. The compressive, tensile, and shear stress on the wall were checked and compared to the wall strength to predict the adequacy of the wall thickness of the plan. The numerical compressive stresses were compared to the compressive strength of the masonry (f'_m). In Indonesia, there is no regulation regarding tensile stress and shear stress allowable for masonry, so this study used building codes of another country as a reference. According to [6], the tensile stress of masonry for solid units should not exceed of 0.414 MPa, and the shear stress of masonry should not exceed of 0.827 MPa and:

$$1.5\sqrt{f'_m} \quad (2)$$

$$v + 0.45N_v / A_v \quad (3)$$

where F'_m = compressive strength of masonry, v = shear stress for masonry in running bond or grouted solid is 0.414 MPa, N_v = compressive force acting normal to shear surface, A_v =

cross-sectional area of shear reinforcement

In addition to stress, drift ratio of the CM structure was also checked using the code of other countries as a reference. According to [7], the drift ratio of buildings with the CM concept must be less than or equal to 0.002 (0.2%).

2.1 Modelling techniques

Shell element is the type of element used to model the behavior of shell, membrane, and plate in the plane and three-dimensional structures. In this study, the wall, tie column, beam, and slab were modeled as a shell element as defined in SAP2000 [8]. The shell element in this finite element model was divided into the small mesh in order to achieve analysis results that are close to the exact solutions. To validate the modeling technique, a different approach was also used, in which the tie-column and beam were modeled as a frame element. The interface between the frame and shell element was modeled as a gap element proposed by [9].

2.2 Modulus of elasticity and cracked moment of inertia

The modulus of elasticity or Young's Modulus is the most important property of a material to measure its stiffness. According to [10], modulus elasticity of normal concrete is given in Eq. 4. For the wall, there is some formula available to calculate modulus elasticity of masonry. This paper referred to MIA, 1998 in [11] to determine the modulus of elasticity of masonry as shown in Eq. 5.

$$E_c = 4700(f'_c)^{0.5} \quad (4)$$

$$E_m = 750f'_m \quad (5)$$

The structural elements are expected to be cracked due to strong earthquakes so that the inertia of the elements will be reduced or less than the gross section. According to [10], the minimum cross-sectional inertia for the beam is 0.35 of the gross moment of inertia (I_g), while for the column it is 0.7 I_g .

2.3 Load

The applied loads on the model structure consist of dead load, live load and earthquake load. According to [11], the live loads are 1.92 kN/m² and 0.96 kN/m² for the floor and roof, respectively. The design coefficients and factors for seismic force-resisting systems did not include the CM structure. Accordingly, values for special reinforced masonry shear walls following [12] were used where the response modification coefficient (R) = 5, over strength factor (Ω_0) = 2.5 and deflection amplification factor (C_d) = 3.5. The site class of the multi-story building model is D with the risk category of buildings is II and its seismic importance factors (I_e) is 1.0.

The values of spectral response acceleration (S_s) and the spectral response acceleration in 1 second (S_1) are depend on the site of building [13]. For buildings located in Denpasar, Bali, $S_s = 0.977$ and $S_1 = 0.360$. Based on these seismic design values, the earthquake loadings are determined using the static equivalent method.

2.3 Validation model

The validation of the modeling technique was done before the modeling of the 3-story CM building. Two approaches were used, where the first model utilized shell element for entire elements include wall, beams, and tie-columns, called Model Shell (MS) and the second model combined the use of frame and shell elements, called Model Frame (MF). In the MF, the frame element is used to model both the beams and columns, while the gap element is used as a connection between the frame and shell elements.

3 Results and discussion

3.1 Validation model

The results of the validation models were shown in Fig. 1 and Fig. 2. Fig. 1 shows both the MS and MF models with the same dimension and materials properties as those of the test data [4]. The modulus of elasticity of concrete (E_c), the modulus of elasticity of masonry (E_m), and the crack moment of inertia (I_{cr}) for columns and beams were varied according to the magnitude of loads. E_c was varied from 19,985 MPa to 1,017 MPa, and E_m was varied from 2,151 MPa to 109 MPa. The I_{cr} values that are ranging between 0.8-0.1 of the gross moment of inertia were used starting after the crack load, as recorded during the test.

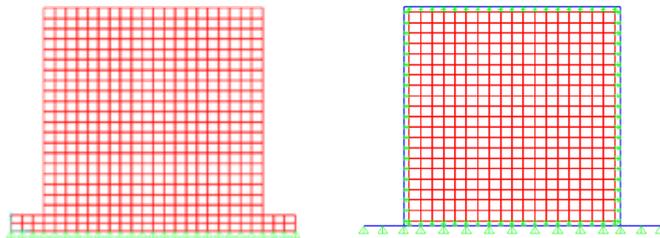


Fig. 1. Validation models: MS (left) use shell element for beam and tie-column, MF (right) use frame element for beam and tie-column.

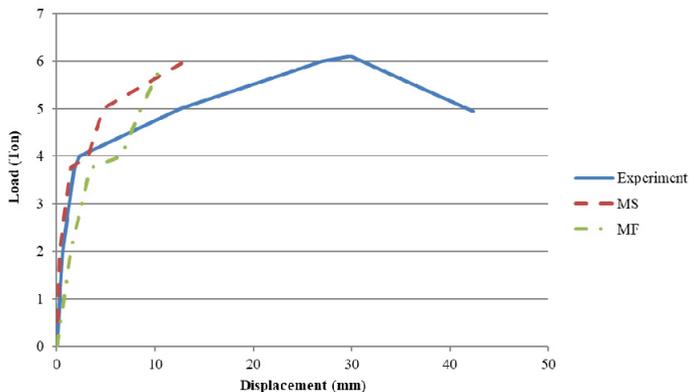


Fig. 2. Load-displacement curve of validation model and experiment results.

The analysis results in Fig. 2 shows the load-deformation curves of the MS and MF models that are plotted together with the experimental test data. It is apparent from Fig. 2 that the MS model mimics the lower part of test data, which indicates the linear behavior, better than that of MF. Before reaching the peak load, it appears that MS has a slightly

smaller displacement than that of the experimental, indicating that the MS is stiffer than the tested specimen. The MF, however, was much more flexible than the test data. Accordingly, the shell element model is a better approach than that of MF and was used to model the 3-story building.

3.2 Model of 3-story residential building

The typical floor plan of the 3-story building model is shown in Fig. 3. Tie-columns were used at the ends of the wall. For the long wall, tie-columns were added to reduce the size of the wall panel. The 3-dimensional SAP2000 model of the 3-story building is shown in Fig. 4. The concrete strength, f'_c was 20 MPa and the masonry strength, f'_m was 3 MPa. The corresponding E_c and E_m were calculated using Eq. 4 and 5.

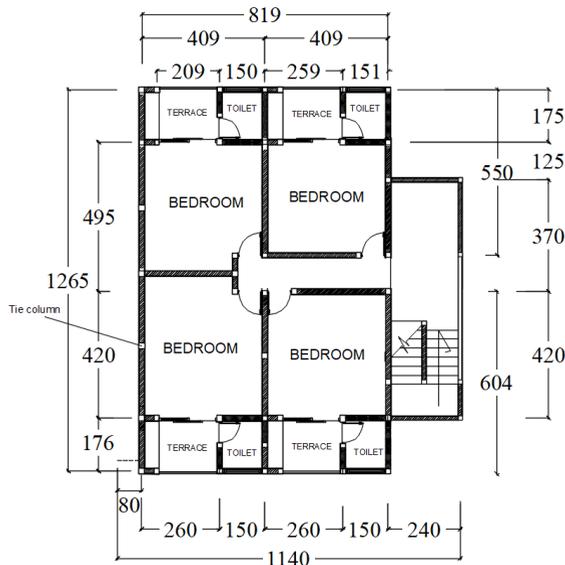


Fig. 3. Typical floor plan of 3-story residential building using confined masonry (CM).

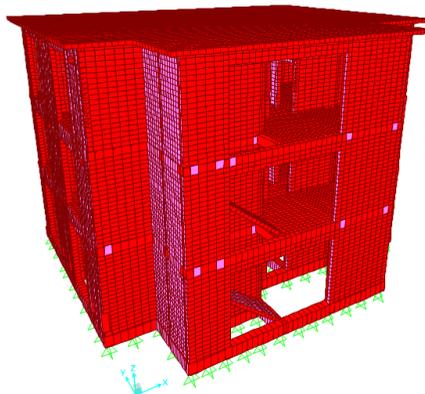


Fig. 4. The 3-D model of 3-story CM Building.

The thickness of the wall was designed according to WDI in Eq. 1. In the x-direction, using wall thickness of 200 mm, 180 mm, 160 mm for 1st, 2nd, 3rd floor, respectively give

WDI-x of 2.55%, 2.30%, and 2.04%. In y-direction, WDI-y of 1.56%, 1.42%, and 1.13% were obtained using a wall thickness of 220 mm, 200 mm, 160 mm for 1st, 2nd, and 3rd floor, respectively. Compared to the code of India in [3] the value of WDI-x of the 1st floor is less than the code value. For the WDI-y of 1st and 2nd-floor values were also below the recommended value.

The dimension of columns and beams are equal to the wall thickness. The height of beams in X and Y direction for 1st, 2nd, and 3rd floor was 300 mm, 250 mm, and 200 mm, respectively. No secondary beam was used to avoid the effect of the concentrated load on the wall.

The contour of stresses on the masonry wall due to the vertical load combination of $1.2D + 1.6L$ are shown in Fig. 5. The maximum stress was observed at the interface between the tie column and the wall with values of 0.26 MPa in tension and 0.05 MPa in compression. Fig. 6 shows stresses due to combined vertical and earthquake loads ($1.2D + 1L + 1Q_x + 0.3Q_y$ and $1.2D + 1L + 0.3Q_x + 1Q_y$). The maximum wall stress was 0.61 MPa in tension and 0.17 MPa in compression. Compared to the tensile strength of 0.414 MPa according to [6] the wall is not safe from tensile cracking.

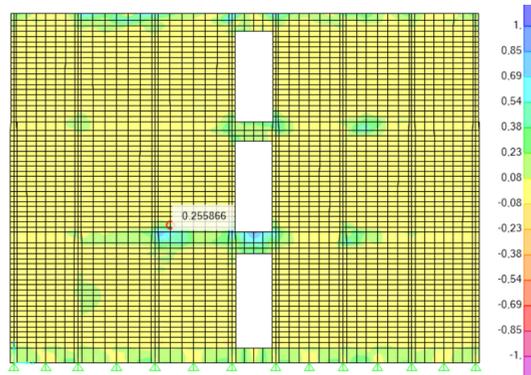


Fig. 5. Max stress (S_{max}) on the masonry wall due to vertical load.

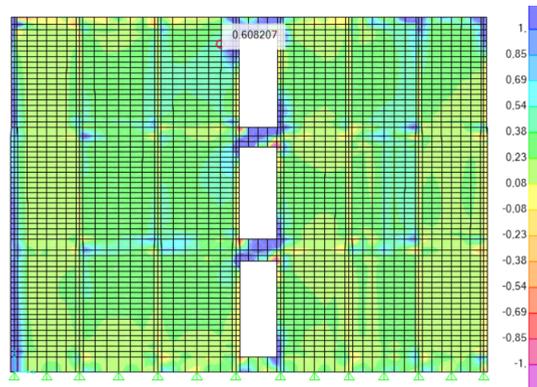


Fig. 6. Max stress (S_{max}) on the masonry wall due to combined vertical and lateral load.

The maximum stress observed was at the corner of the opening. The maximum value was 1.80 MPa in tension and 0.53 MPa in compression. As the corners of the walls were confined with reinforced concrete beams and tie-columns, it will not be cracked. Otherwise, these corners will be cracked as commonly observed in the corners of opening on masonry walls. This justifies the need for the confinement of the wall along the opening.

The maximum shear stress on the wall is 0.08 MPa due to vertical load and 0.55 MPa due to combined vertical and lateral loads. The allowable shear stress was 0.827 MPa according to [6]. Therefore, the wall is safe from shear failure.

The maximum tensile stress on the concrete beam was 0.94 MPa and 5.66 MPa due to vertical and combined vertical and lateral load, respectively. The corresponding values for compressive stresses were 0.13 MPa and 1.18 MPa. It is apparent that the tensile strength of 20 MPa concrete of 3 MPa is smaller to the maximum tensile stress. Therefore, cracks occur on the beam due to tensile stresses that exceed the design value.

3.2.1 *Beam and column reinforcement*

The average tensile stress on the 3rd-floor beam is 2.66 MPa and 2.98 MPa for the column. The tensile reinforcement was calculated based on the average stresses. The tensile reinforcement of beam and column on the 1st, 2nd, and 3rd of grid C was 4D13. Besides tensile stress, the shear stress was also checked to determine the need for stirrups. Average shear stress on the 3rd-floor beam is 1.28 MPa and 1.01 MPa for the column. The required shear reinforcement was minimum according to the code [9] which is $\phi 10$ with 200 mm spacing. Compared to the RC frame structure (more commonly used for 3-story building), the reinforcement for CM structure was much less than the requirement for RC frame structure. Also, the size of beams and columns are larger for the RC frame. Accordingly, the use of CM structure for the simple residential building may lead to lower cost of construction.

3.2.2 *Drift ratio*

As expected, the story displacement of the 3-story model was very small. The rooftop displacement due to combined vertical and lateral loads was 4.39 mm and 5.53 mm for x and y-direction, respectively. The corresponding drift ratio was 0.05% in the x-direction, and 0.06% in the y-direction, much lower than the limiting value suggested in the literature [7] of 0.2%. This means that the model was very stiff despite the values of WDI used were less than that suggested in the codes of another country. The small drift ratio also a measure of safety of the non-structural component of building under seismic loads.

4 Conclusions

The method of modeling CM structure using shell element for masonry walls and RC column and beams produced load-deformation curve that mimics the lower part of the curve of the tested specimen better than that using frame and shell elements. The modeling technique was then applied for the analysis and design of the 3-story residential building with seismic design category D in the Denpasar area.

Using wall density index (WDI) less than the value suggested in the building codes of foreign countries, the CM model appears very strong and stiff. The maximum wall stresses under seismic design load were still less than the wall strength. The maximum tensile stress was observed at the corner of opening that justify the importance of tie-column to confine and strengthen the wall. Also, the maximum drift ratio of the 3-story model was 0.06%, much smaller than the code limit of 0.2%. This means that the adoption of confined masonry technology in the construction of single housing may lead to safer buildings at lower construction costs compared to alternative options.

Further research is necessary to determine a value for WDI for application of CM in Indonesia because the value suggested in the literature seems very high. Also, it is necessary to investigate alternative modeling techniques such as using solid element.

Modeling the wall as strut and tie also worth trying, especially when the inelastic response is of interest. It is hoped that this paper will contribute to the attempts of popularizing the use of confined masonry in Indonesia and have a far-reaching impact on the construction industry throughout the country and beyond.

References

1. Swiss Agency for Development Cooperation. *Confined masonry*. Available at: <https://logementquartierhaiti.files.wordpress.com/2011/10/confined-masonry-training-pakistan.pdf> (2006)
2. S.K. Jain, S. Brzev, L.K. Bhargava, D. Basu, I. Ghosh, D.C. Rai, K.V. Ghaisas, *Confined masonry for residential construction* (NITG, Gandhinagar, 2015)
3. S. Brzev, *Earthquake-resistant confined masonry construction* (NICEE, Kanpur, 2007)
4. C.B. Bachroni, J. Perumahan **8**, 1 (2013)
5. NTCM, *Complementary technical standards for design and construction of masonry structures* (Spanish) (Building Regulations for the Federal District, Official Gazette of the Department of the Federal District, Mexico, 2004)
6. ACI, *Building code requirements for masonry structures* ACI 530-02 (American Concrete Institute, Farmington Hill, 2002)
7. INN, *Confined masonry-requirements for design and calculation* (Spanish) (National Standard Institute, Cile, 1997)
8. CSI, *Analysis reference manuals for SAP2000, ETABS, SAFE and CSiBridge*, (Computer and Structures Inc, Berkeley, 2011)
9. J. Dorji, D.P. Thambiratnam, *The Open Con. and Build. Tech. J.* **3** (2009)
10. ACI, *Building code requirements for structural concrete* ACI 318M-11 (American Concrete Institute, Farmington Hill, 2011)
11. P. Agarwal, M. Shrikhande, *Earthquake resistant design of structure* (PHI Learning Private Ltd, New Delhi, 2006)
12. ASCE, *Minimum design loads for buildings and others structures* ASCE/SEI 7-10 (American Society of Civil Engineering, Virginia, 2011)
13. Pusat Litbang Perumahan dan Perumahan Kementerian PUPR, *Desain Spektra Indonesia*. Available at: http://puskim.pu.go.id/Aplikasi/desain_spektra_indonesia_2011/