Nonlinear Modeling of Confined Masonry Structures Using Layered Shell Elements

I Gusti Bagus Michael Satria Dwipayana[1*], Made Sukrawa[1], Ida Ayu Made Budiwati[1]
Undergraduate Program in Civil Engineering, Faculty of Engineering, Universitas Udayana, Jimbaran, Bali, Indonesia[1]
*Corresponding author e-mail address: mikel100904@gmail.com

ABSTRACT

Confined masonry structures are widely used in simple buildings located in seismic regions; however, their behavior is difficult to represent numerically because masonry is heterogeneous and nonlinear. This study evaluates layered shell elements in SAP2000 for modeling the global response of confined masonry, analyzes the influence of material parameters, and compares a simple building model based on the guideline of the Ministry of Public Works and Housing of Indonesia (PUPR), hereafter referred to as CM, with an Earthquake Engineering Research Institute (EERI)-based modified model, hereafter referred to as CME. The CME model includes additional reinforcing columns and beams around wall openings. Validation was conducted using two-dimensional and three-dimensional models based on previous laboratory experiments. The investigated parameters include masonry compressive strength (f'm), masonry elastic modulus (Em), masonry shear modulus (Gm), and concrete compressive strength of confining elements (f'c). The results show that layered shell elements can represent the global response of confined masonry structures, particularly initial stiffness, lateral capacity, and stress concentration patterns, although the analysis was conducted using monotonic pushover loading. The sensitivity analysis indicates that the parameter influence, from the lowest to the highest, is f'c, f'm, Em, and Gm. In the application model, both CM and CME reach the Immediate Occupancy (IO) performance level. However, CME produces smaller drift, higher lateral capacity, and a more uniform wall stress distribution than CM. Therefore, the EERI-based modification can increase lateral capacity and control local damage in confined masonry structures.

Keywords: confined masonry structure, EERI, layered shell, material sensitivity, pushover.

1. INTRODUCTION

Confined masonry structures are widely used in simple buildings located in seismic regions because masonry walls and reinforced concrete confining elements work together to resist lateral loads [1]. However, their behavior is difficult to model numerically because masonry is heterogeneous, nonlinear, and prone to cracking in critical areas, particularly around wall openings [2], [3].

Several studies have modeled confined masonry using shell elements, solid elements, and other numerical approaches [4], [5]. Nevertheless, these approaches still have limitations, particularly in practical application to three-dimensional building models. Layered shell elements in SAP2000 offer an alternative because they can represent masonry walls, confining concrete, and reinforcement within a practical modeling system [6].

In addition to the modeling approach, the numerical response of confined masonry is also affected by material parameters such as masonry compressive strength, elastic modulus, shear modulus, and concrete compressive strength of the confining elements. Therefore, a sensitivity analysis is required to identify the parameters that most influence initial stiffness, lateral capacity, and stress distribution.

This study aims to evaluate the capability of SAP2000 layered shell elements through 2D and 3D validation models, analyze the sensitivity of material parameters, and compare a simple confined masonry model based on PUPR with a modified model based on EERI. The comparison is conducted in terms of drift, lateral capacity, performance level, stress distribution, and damage mechanism.

2. THEORY AND METHODS

2.1 THEORY

Confined masonry is a structural system that relies on the interaction between masonry walls and reinforced concrete confining elements. In this system, the wall does not merely act as an infill element but also contributes to resisting lateral loads. Therefore, the behavior of confined masonry is strongly influenced by masonry properties, confining elements, and wall-opening configuration [1], [2].

Wall Opening and Reinforcement

Wall openings can cause stress concentration around opening corners and may initiate tensile or shear cracking. This principle forms the basis for the CME modification, namely the addition of reinforcing columns and beams around openings based on EERI recommendations, which is then compared with the CM model following the PUPR guideline [1], [3].

Layered Shell Element

Numerical modeling of confined masonry requires an approach capable of representing the nonlinear behavior of masonry. Layered shell elements are used because they can model masonry walls, confining concrete, and reinforcement as different material layers within a single area element. This approach is more practical for three-dimensional models than solid elements and enables the evaluation of both global response and local stress distribution [4], [5].

Material Parameters

Besides the element type, material parameters also affect the model response. Masonry compressive strength, elastic modulus, shear modulus, and concrete compressive strength influence initial stiffness, lateral capacity, and stress patterns. The masonry shear modulus is important because it is directly related to wall shear deformation and needs to be calibrated against experimental results [6].

Performance Analysis

Structural performance is evaluated through pushover analysis to obtain the capacity curve, performance level, and damage mechanism. The evaluation is carried out not only globally but also through stress checks in the walls, concrete, and reinforcement to assess local damage in critical areas.

2.2 METHODS

This study was conducted numerically using SAP2000 with layered shell elements to model masonry walls, concrete confining elements, and steel reinforcement. The initial stage consisted of 2D and 3D validation models accompanied by material-parameter sensitivity analysis. In the 2D validation, two models were used: MSh as the confined masonry panel without opening and MSh-WO (Model Shell-With Opening) as the confined masonry panel with an opening. Meanwhile, the 3D validation used MSh-3D, a three-dimensional confined masonry model used to evaluate the spatial global response of the structure. The 2D validation refers to the experiment by Suarjana et al. [1], whereas the 3D validation refers to the experiment by Ahmed et al. [2]. Model agreement was evaluated using load-displacement curves, initial stiffness, lateral capacity, and stress distribution patterns in critical areas.

During validation, sensitivity analysis was performed on masonry compressive strength, masonry elastic modulus, masonry shear modulus, and concrete compressive strength of the confining elements. This analysis was used to determine the influence of each parameter on the model response. The parameter with the greatest influence was then calibrated so that the numerical response approached the experimental results.

After the validation models were considered capable of representing the global response of confined masonry, the modeling method was applied to a simple 3D confined masonry building. The application model consisted of CM, which follows the PUPR guideline [3], and CME, which is modified based on EERI recommendations [4]. The modification in the CME model consists of additional reinforcing columns and beams around wall openings. Because the application models were developed as three-dimensional models, the calibrated masonry shear modulus obtained from the 3D validation, $G_m = 0.40E_m$, was used for the masonry walls in both CM and CME. Both models were then analyzed under gravity loads, seismic loads, and pushover analysis in the X and Y directions. The results were compared based on drift, lateral capacity, performance level, wall stress distribution, confining-element stress, and local damage mechanism.

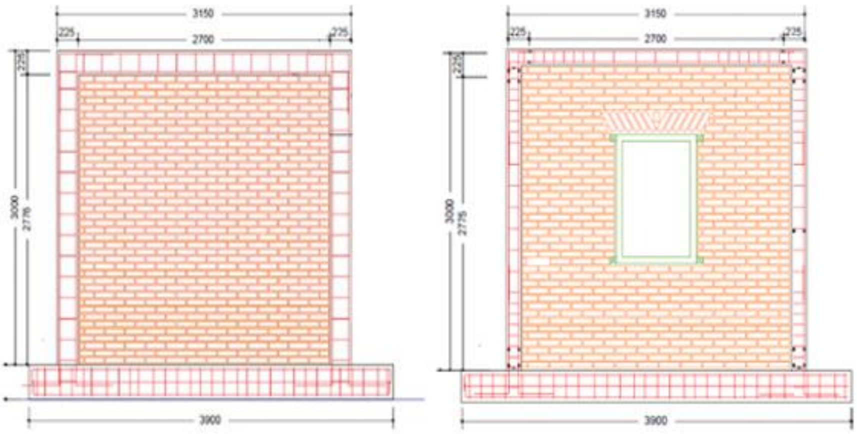
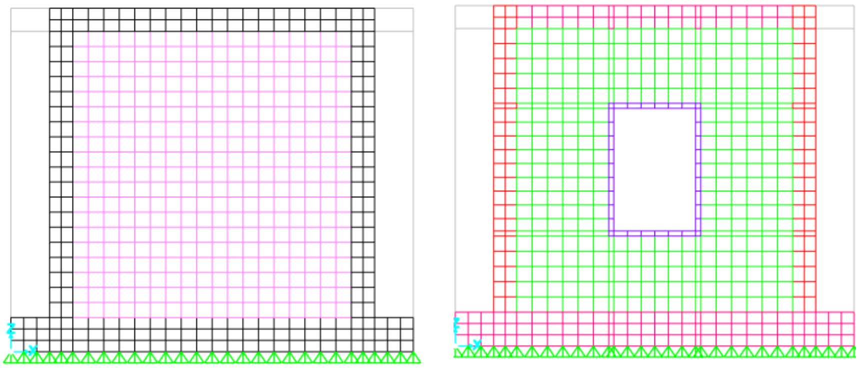
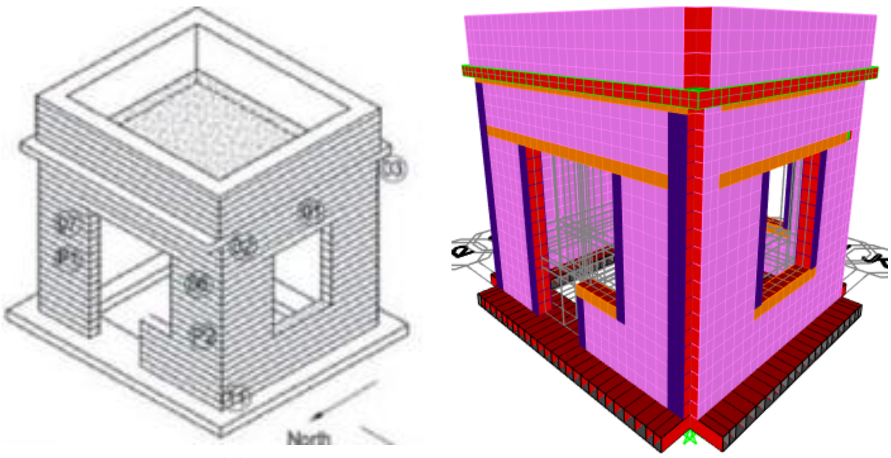


Figure 1. Experimental 2D models by Suarjana et al. (2012)



(a) (b)

Figure 2. 2D validation models (a) Msh and (b) Msh-WO



(a) (b)

Figure 3. (a) Experimental 3D model by Ahmed (2019) and (b) 3D validation model

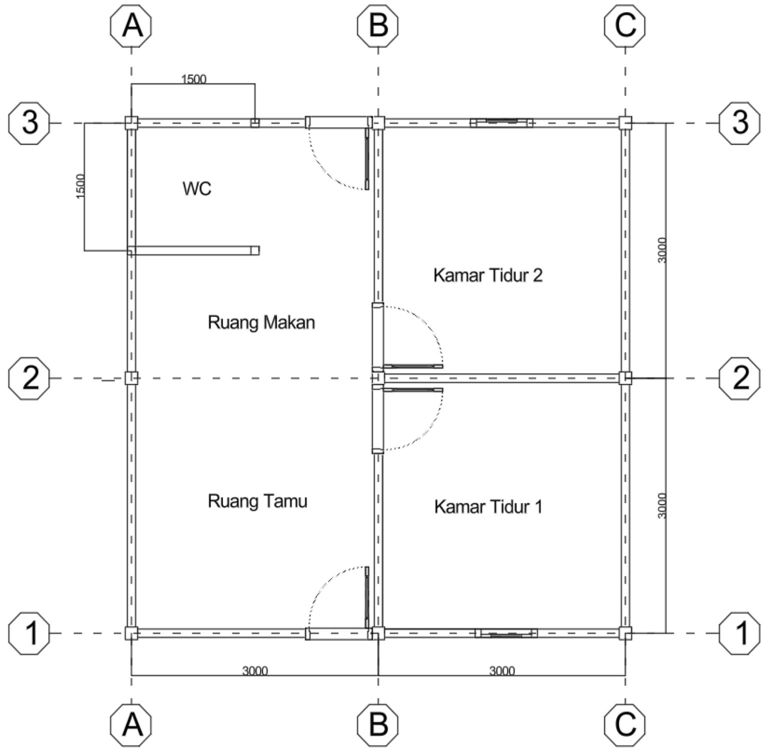


Figure 4. Plan of the 3D confined masonry application model

3. RESULTS AND DISCUSSION

3.1 VALIDATION OF THE 2D CONFINED MASONRY MODEL

The 2D validation results show that the layered shell element can follow the global response tendency of confined masonry panels based on the load-displacement curve, although the model response remains stiffer than the experimental response in the post-cracking stage. This difference is caused by the loading scheme, because the numerical model uses monotonic pushover loading, whereas the experiment uses cyclic loading, which causes damage accumulation and stiffness degradation.

The sensitivity analysis shows that Gm is the parameter that most influences lateral stiffness and the curve shape. The trial calibration indicates that Gm = 0.01Em provides the closest response to the 2D experiment; therefore, this value is used as an effective model parameter. The stress check does not fully represent the actual cracks because the numerical stresses remain relatively small. However, the stress-concentration locations are consistent with the experimental crack pattern, namely along the wall diagonal and around the opening corners.

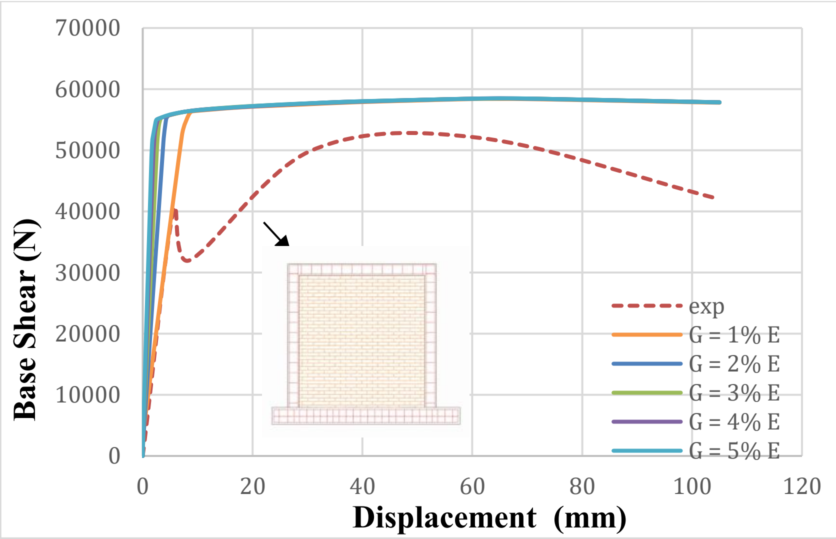


Figure 5. Trial calibration of Gm for the MSh model

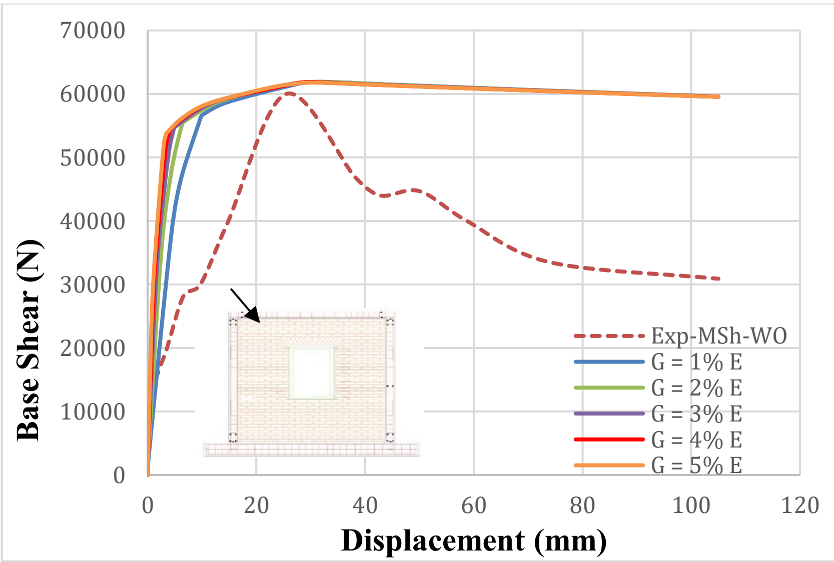
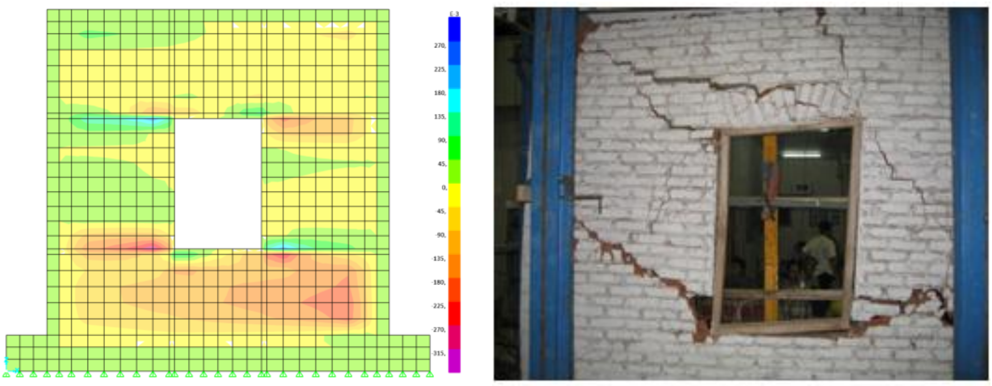


Figure 6. Trial calibration of Gm for the MSh-WO model



(a) (b)

Figure 7. (a) Stress concentration in the MSh-WO model and (b) experimental crack pattern

3.2 VALIDATION OF THE 3D CONFINED MASONRY MODEL

The 3D validation results show that the layered shell element can follow the global structural response tendency based on the load-displacement curve, although the model is still stiffer than the experiment in the post-cracking stage. This difference is influenced by the loading scheme, because the numerical model uses monotonic pushover loading, whereas the experiment uses cyclic loading that causes damage accumulation and stiffness degradation.

Based on the sensitivity analysis, Gm is the parameter that most affects the curve shape, and Gm = 0.40Em provides the closest response to the 3D experiment; therefore, this value is used as the effective model parameter. The stress check does not fully describe the actual cracks because the numerical stress values remain relatively small. However, the stress-concentration locations are consistent with the experimental damage pattern, particularly around openings, wall corners, and wall-confining element intersections.

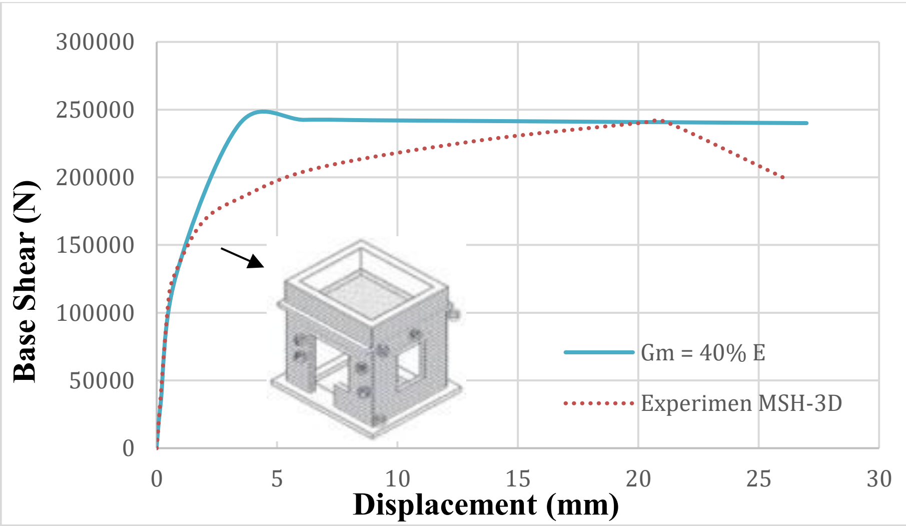
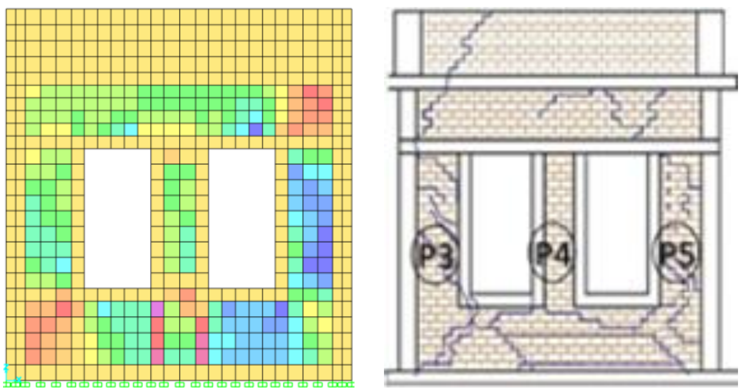


Figure 8. Load-displacement curve of the MSh-3D analysis and experiment

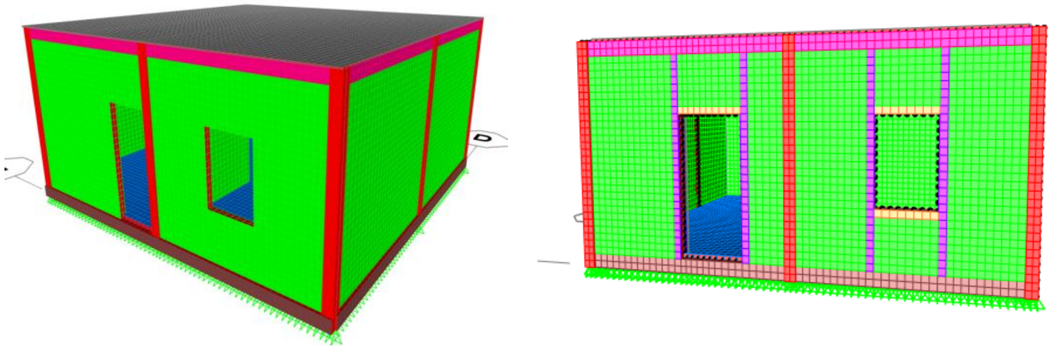


(a) (b)

Figure 9. (a) Stress concentration in the 3D model and (b) experimental damage pattern

3.3 RESPONSE OF THE APPLICATION MODEL UNDER DESIGN LOAD

The application model consists of CM based on PUPR and CME modified according to EERI through the addition of reinforcing elements around openings. Under the design load, the response of both models is evaluated through structural period, drift, and stress checks.



(a) (b)

Figure 10. 3D confined masonry application models: (a) CM and (b) CME

The analysis results show that the structural periods of CM and CME are almost the same; therefore, the CME modification does not significantly change the dynamic characteristics of the structure. However, based on Figure 11, the drift of the CME model is smaller than that of CM in both X and Y directions. This indicates that the additional reinforcing elements increase the lateral stiffness of the model.

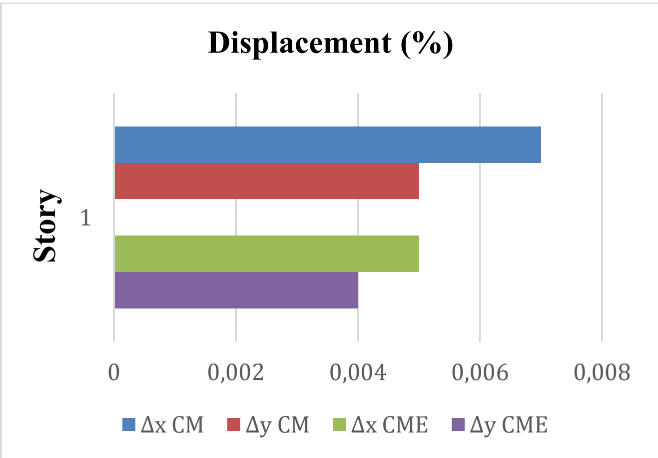


Figure 11. Drift comparison of CM and CME under design load

Based on Tables 1 and 2, the stresses in the wall, concrete, and reinforcement of both CM and CME remain below the material allowable limits. However, CME produces smaller wall stress, especially tensile stress. Therefore, under the design load, both models are still safe, while CME shows a more controlled stress distribution.

Table 1. Wall stress recap under design load

Model	Condition	Comp.	Tens.	Shear	Status
CM	Design load	0,337	0,221	0,108	Safe
CME	Design load	0,104	0,102	0,076	Safe

Table 2. Confining element stress recap under design load

Model	Condition	Concrete		Reinforcement		Status
		min	max	min	max	
CM	Design load	-0,70	0,30	-11	6,01	Safe
CME	Design load	-1,42	0,62	-10,04	4,56	Safe

3.4 PUSHOVER ANALYSIS AND PERFORMANCE LEVEL

The pushover analysis results for CM and CME are shown in Figure 12. The graph presents the relationship between base shear and lateral displacement in the X and Y directions. Based on the capacity curves, both models have lateral capacities greater than the design seismic base shear and both models reach the Immediate Occupancy (IO) performance level. However, CME shows a higher lateral capacity and smaller drift than CM, indicating a stronger and stiffer response.

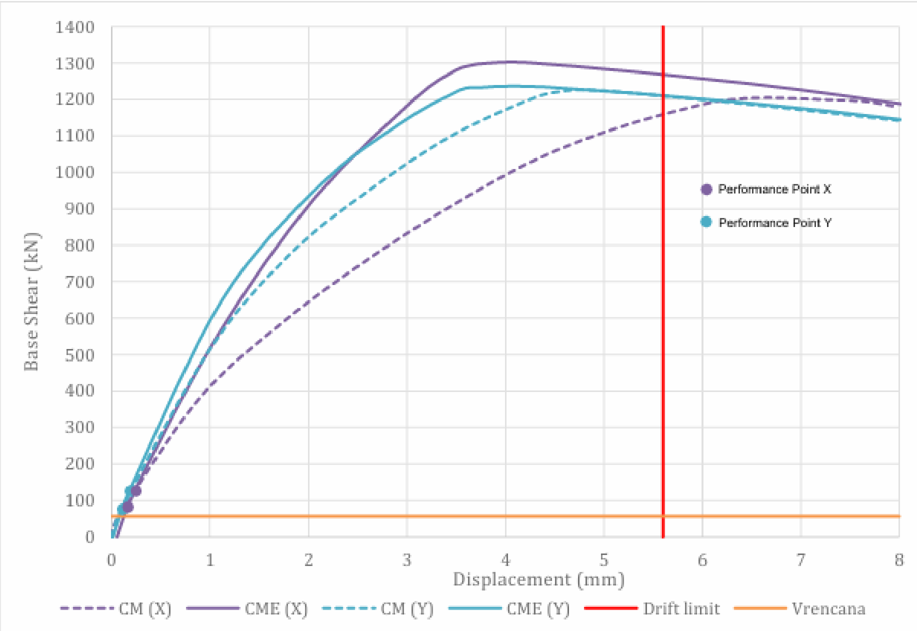


Figure 12. Pushover capacity curves of CM and CME

3.5 STRESS CHECK AT PERFORMANCE POINT AND DEFORMATION LIMIT

Stress checks at the performance point and deformation limit were conducted to evaluate the local behavior of CM and CME. The wall stress recaps in the X and Y directions are shown in Tables 3 and 4, while the concrete and reinforcement stresses of the confining elements are shown in Table 5.

At the performance point, CME shows lower and more uniform wall stresses than CM. In CM, tensile and shear stresses have reached critical conditions, whereas in CME the compressive, tensile, and shear stresses remain below the allowable limits. This indicates that although both models are at the Immediate Occupancy (IO) performance level, the local wall response of CME is more controlled.

At the deformation limit, CM reaches critical conditions in wall compressive, tensile, and shear stresses. In contrast, in CME the compressive stress remains below the allowable limit, although tensile and shear stresses have reached critical conditions. This condition indicates that the CME modification can delay compressive damage and produce a more controlled damage mechanism.

Table 3. Wall stress recap of CM and CME in the X-direction pushover

Model	Condition	Comp.	Tens.	Shear	Status
CM	Performance point	1,222	0,791	0,452	Tension and shear failure
CME	Performance point	0,241	0,261	0,242	Safe
CM	Deformation limit	3,352	1,722	0,815	Compression, tension, and shear failure
CME	Deformation limit	0,771	0,624	0,552	Tension and shear failure

Table 4. Wall stress recap of CM and CME in the Y-direction pushover

Model	Condition	Comp.	Tens.	Shear	Status
CM	Performance point	0,781	0,665	0,372	Tension and shear failure
CME	Performance point	0,281	0,292	0,252	Safe
CM	Deformation limit	2,651	1,402	1,112	Compression, tension, and shear failure
CME	Deformation limit	0,820	0,455	0,607	Tension and shear failure

For the confining elements, the performance point is dominated by concrete tensile failure, while the reinforcement has not yielded. At the deformation limit, the reinforcement stresses in CM and CME exceed the yield stress, indicating that the confining elements start to work inelastically due to force redistribution from the locally damaged wall.

Table 5. Stress recap of confining elements in CM and CME

Model	Condition	Concrete		Reinforcement		Status
		min	max	min	max	
CM	Performance point	-4,6	3,13	-14,43	264,63	Tensile failure in concrete
CME	Performance point	-8,12	2,61	-134,21	213,62	Tensile failure in concrete
CM	Deformation limit	-15,1	3,16	-366	419	Failure in concrete and reinforcement
CME	Deformation limit	-15,2	3,14	-319	451	Failure in concrete and reinforcement

4. CONCLUSIONS

Based on the validation, sensitivity analysis, and application model results, layered shell elements in SAP2000 can represent the global response of confined masonry structures reasonably well. This is indicated by the model capability to follow the initial stiffness tendency, lateral capacity, and stress-concentration locations of the 2D and 3D experimental models. Differences in the post-cracking response still occur because this study uses monotonic pushover loading, whereas the experiments use cyclic loading. Nevertheless, the model can still show damage-location tendencies consistent with the experimental results.

The sensitivity analysis shows that the masonry shear modulus (Gm) has the greatest influence on the response of the confined masonry model. The sensitivity order of the parameters from the lowest to the highest is f'c, f'm, Em, and Gm. The effective Gm values that provide the most suitable responses are 0.01Em for the 2D validation model and 0.40Em for the 3D validation model. This indicates that Gm should be treated as a calibration parameter in numerical modeling of confined masonry, not as a universal material value.

In the application model, both CM and CME have lateral capacities greater than the design seismic base shear and reach the Immediate Occupancy (IO) performance level. However, CME produces higher lateral capacity, smaller drift, and a more uniform wall stress distribution than CM, particularly around openings. Therefore, the EERI-based modification through additional reinforcing elements around openings affects the improvement of global response and local stress control in simple confined masonry structures. Future studies are recommended to use cyclic loading so that stiffness degradation and crack development can be represented closer to experimental behavior.

5. ACKNOWLEDGEMENTS

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