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Numerical study of confined masonry structure considering wall density index

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Abstract. The confined wall structure (CWS) of medium-rise buildings are generally built with walls of the same thickness. It causes stress at the bottom wall-story to become the highest. Numerical analysis was conducted to evaluate the behavior of CWS with wall density index variations. Three 4-story CWS buildings with different wall thicknesses were modeled in finite element software. Model 1 (M1) considered the same wall thickness for the whole building; M2 and M3 varied the thickness where the top floor wall was the thinnest. The calculation of wall density index (WDI) was performed on all three models. The results showed that the value of WDI calculated using the transformation method is the closest because it takes into account the differences in material quality and its value meets the standard requirements. Analysis results showed that the drift ratio for all three models were less than 0.2%, which also fulfilled the requirement. However, M3 showed the highest displacement. Compressive stress, tensile stress, and shear stress for M1 and M3 models satisfied the allowable stresses, but maximum compressive stress on the top-level wall of M2 exceeded the permitted stress.

1. Introduction

Earthquake-resistant building structures are needed in Indonesia, as most of the country's area is vulnerable to earthquakes. Confined wall structure (CWS) is a structure consisting of brick walls with restraints in the form of column and beam elements on all four sides. These structural elements can reduce cracks due to seismic responses during an earthquake, preventing structural destruction even in large earthquakes [1].

CWS is widely applied in various earthquake-prone countries such as Slovenia, India, Chile, and China [2], but in Indonesia, it has not been applied to multilevel buildings. This needs to be reviewed, considering that the CWS is very potential to be applied in Indonesia, where most of the area is prone to earthquakes. Building CWS requires a lower cost compared to the structure of reinforced concrete frame walls, as the role of the wall in CWS is increased while the frame role is reduced, causing a smaller use of frame dimension resulting in reduced construction costs.

One of the factors that influence the seismic resistance of the CWS is the wall density index or WDI [3]. CWS planning with WDI that complies with regulations can increase earthquake resistance. However, the definition of WDI is still unclear as there are several ways to calculate the WDI. Also, Indonesia does not yet have regulations regarding the CWS and therefore needs to be reviewed.

CWS has been applied to the construction of dormitories at the Indian Institute of Technology Gandhinagar (IITG), precisely in Gujarat India. Nonetheless, the IITG dormitory building was built with the same wall thickness on all floors allowing the stress to occur at the largest ground floor.



Therefore, it is necessary to do further research with varied WDI by varying the wall thickness so that the expected stress on each floor is not much different.

CWS can be modeled with shell element, solid element, plate element, strut and tie, where a shell element model will be used in this study. The previous researches have shown that CWS modeling using shell elements to obtain displacement results is close to testing results [4, 5, 6]. Based on the description, the study of the behavior of CWS with wall density variations using shell elements model will be carried out.

2. Confined Wall Structure

The confined wall structure (CWS) is a wall structure composed of masonry with horizontal and vertical restraints on all four sides. This restraint element effectively increases the strength of the masonry walls in resisting earthquake loads. The stages of construction of the CWS, namely masonry walls are built first, after which casting the tie-columns in situ is followed by casting of tie-beams on the wall together with the construction of the floor/slab. A simple form of the building is one of the main requirements in planning a CWS that can withstand earthquakes.

The CWS capability in carrying loads is controlled through the deviation and voltage that occurs. The deviation of each floor is observed; then, the drift ratio is calculated from the deviation. The drift ratio must be controlled to ensure that the drift ratio does not exceed the requirements. Based on Chile's regulation NCh 2123.Of97 [7], the drift ratio of buildings with the concept of confined walls must be less than or equal to 0.002 (0.2%). The voltage-controlled is compressive stress, tensile stress, and shear stress. The compressive stress that occurs is expected not to exceed the quality of the wall pair so that there are no cracks in the wall. At present, the regulations in Indonesia governing the tensile stress and shear stress of confined wall permits are not yet available. Therefore, in this study, the Building Code Requirements for Masonry Structures [8] was used as a reference. Permitted tensile stress due to bending for clay and concrete walls and solid units with diagonal crack direction is 60 psi (414 kPa) = 0.414 Mpa, while the shear stress must not exceed 0.827 MPa and following equations:

$$1,5 \sqrt{f'm} \quad (1)$$

$$v + 0,45 N_v/A_v \quad (2)$$

where $f'm$ is the masonry compressive strength (MPa), $v = 60$ psi (414 kPa) for grouted masonry, $N_v =$ normal force (N) and $A_v =$ shear cross-sectional area (mm^2).

2.1. Wall Density

Wall density index (WDI) is one of the key factors that influence seismic resistance [2]. WDI is a wide ratio of effective wall support on each floor. Based on past earthquakes, it was shown that adequate CWSs with WDI was able to withstand the effects of earthquakes without experiencing collapse [1]. The value of the WDI must be determined for both building plan directions. The calculation of the WDI value still needs to be studied further as there are several ways to calculate the WDI. WDI is calculated based on Equation 3 and Equation 4 [1, 2].

$$\text{WDI} = (\text{Wall section area}) / (\text{Total floor area}) \times 100\% \quad (3)$$

$$\text{WDI} = (\text{Wall section area}) / (\text{Reviewed floor area}) \times 100\% \quad (4)$$

According to Mexican regulations in [2], the value of WDI (d, %) for 1-5 story building is given in figure 1.

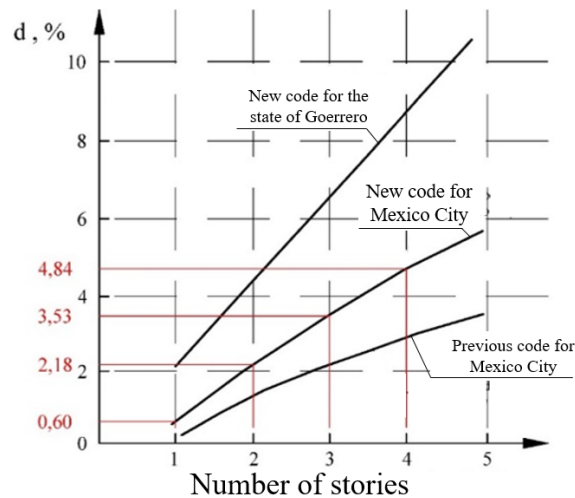


Figure 1. Graph of the relationship of the WDI value with the number of levels.

2.2. Modulus of Elasticity and Moment of Inertial Crack Section

Modulus of Elasticity (E) is a measure of the stiffness of a material. The modulus of elasticity (E) for normal concrete is calculated by Equation 5 [9]. For masonry, there are several formulas for calculating the elastic modulus of the wall. This study refers to Equation 6 [10]

$$E_c = 4700\sqrt{f'_c} \quad (5)$$

$$E_m = 750f'_m \quad (6)$$

In the event of a strong earthquake, structural elements can be fractured so that the cross-section inertia of the element should be reduced. The maximum crack section inertia requirement for beams is 0.35 of the moment of gross inertia (I_g) of the beam, while for column and wall is 0.7.

3. Method

3.1. Validation Model

The validation model refers to the CWS model without openings (V1) and with openings (V2). Material and geometry data are given in tables 1 and 2.

Table 1. Material data.

Material	Concrete	Wall	Wood Frame
Compressive Strength (f'_c)	15.32 MPa	2.33 MPa	9.06 MPa
Modulus of elasticity (E)	18396 MPa	1747 MPa	12258 Mpa

Table 2. The geometry of the validation model.

Element	Tie Beam	Beam	Column	Openings	Wall thickness
Dimension (mm)	332x850	100x225	100x225	800x1200	100

The reduction of inertia moment (I) and elasticity modulus (E) was applied to include the effect of non-linearity of material and geometry of the structure, as given in table 3.

Table 3. Model properties with and without opening.

Load (kN)	Em (MPa)	with opening				without opening			
		Ec (MPa)	Icr			Ec (MPa)	Icr		
			Column	Beam	Column		Column	Beam	Wall
0	1750	18400	1	18400	1	18400	1	1	1
10	1750	18400	1	18400	1	18400	1	1	1
20	1750	18400	1	17300	0,90	17300	0,90	0,90	0,70
30	1440	11380	0,90	11380	0,80	11380	0,80	0,85	0,50
40	1380	10120	0,80	10120	0,80	10120	0,80	0,85	0,35
50	1275	8780	0,70	8780	0,70	8780	0,70	0,80	0,15
55	1045	6900	0,70	6900	0,70	6900	0,70	0,75	0,10

3.2. Application Model

The application model was a 4-story confined wall building (CWS) taken from the dormitory building plan of the Indian Institute of Technology Gandhinagar (IITG), and it was assumed to be built in Denpasar City, Bali. Material Data applied was Concrete compressive strength (C): 20 MPa; Modulus of elasticity of concrete (Ec): 21019 MPa; Masonry compressive strength (fm): 3 MPa; Modulus of elasticity of (Em): 2250 MPa.

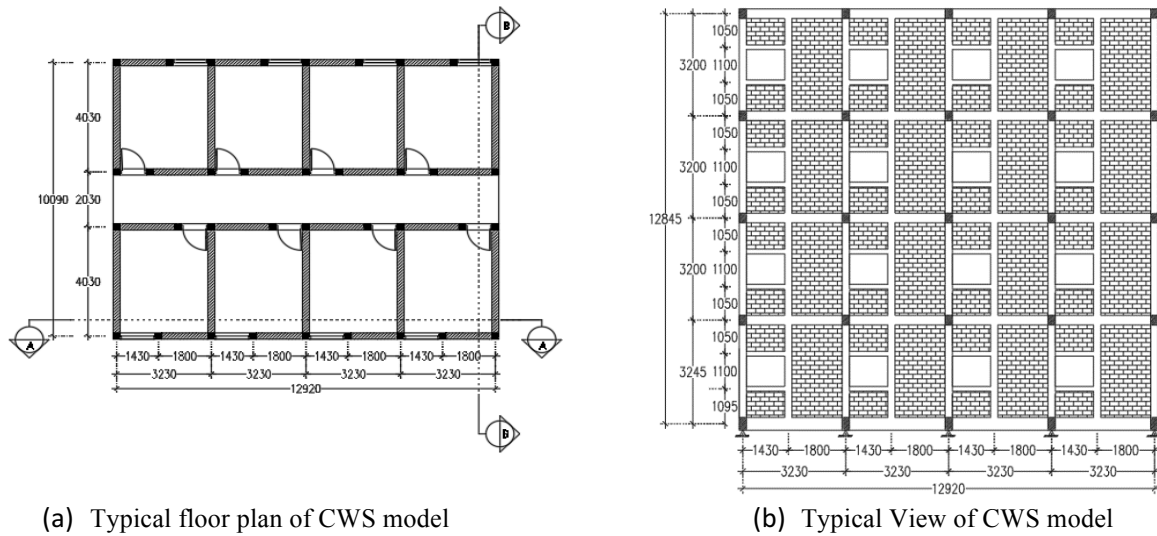
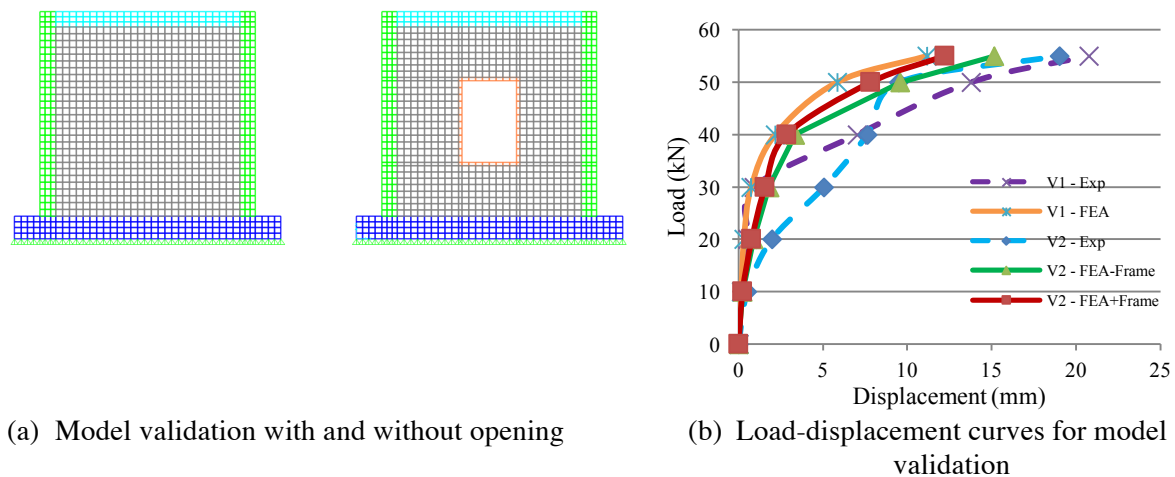
Geometry data of all models are given in table 4. The wall thickness of 230 mm was applied to M1, the same with the existing thickness of the IITG dormitory building. The thickness of other models was chosen based on the practical construction size. The dimensions of columns and beams follow the dimensions of wall thickness with a beam height of 300 mm. Dimensions of tied-beam was 300/400 mm. The typical structure plan and view (Portal A-A) of all models are shown in figure 2.

Table 4. Wall thickness model application.

Level	The thickness of M1		The thickness of M2		The thickness of M3	
	(mm)		(mm)		(mm)	
	X	Y	X	Y	X	Y
	Direction	Direction	Direction	Direction	Direction	Direction
1	230	230	230	230	230	230
2	230	230	180	180	200	200
3	230	230	140	140	180	180
4	230	230	130	130	150	150

4. Results and Discussion

The validation models OF CWS with and without openings are shown in figure 3 (a). Load displacements curves for all models and experiment results are plotted in figure 3 (b). The maximum stresses in the walls are shown in table 5.

**Figure 2.** Portal A-A CWS application model.**Figure 3.** Model validation and load-displacement curves.**Table 5.** Maximum stresses (MPa) of CWS application models.

Stress	Without opening				With opening			
	S11	S22	S12	Smax	S11	S22	S12	Smax
Compressive	-2,36	-2,14		-0,36	-2,22	-2,38		-1,27
Tensile	1,16	2,28		2,48	2,13	2,09		3,05
Shear			0,82				0,84	

From the load-displacement graph, it can be seen that the model's results are close to the experiment one up to the linear portion. Result of the model with a frame around openings is more rigid than without frames; wooden frames provide restraints on the walls. From table 4, it can be seen that the compressive stress, tensile stress, and shear stress that occur is greater than the permit stresses. Cracks occur on the wall due to those stresses.

4.1. Calculations of WDI

There are several ways in calculating the WDI value; however, in this study, it is proposed to use the calculation of the WDI transformation for each level, as shown in Equation 7.

$$\text{WDI} = (\text{Transverse area of transformation wall}) / (\text{floor area level and above}) \times 100\% \quad (7)$$

The calculated value of WDI transformation is the ratio of the cross-sectional area of the walls of each direction to the floor area supported. The calculated WDI values are shown in table 6.

Table 6. WDI for M1.

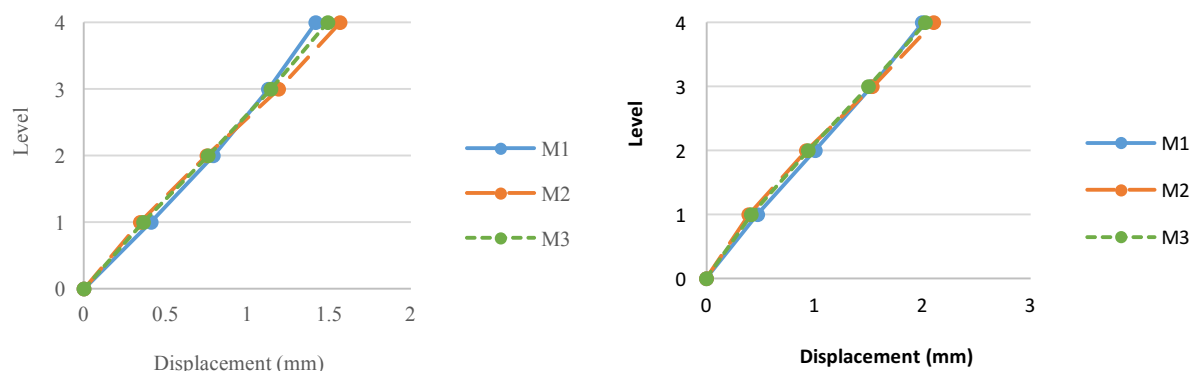
Level	Wall Density Index (WDI)											
	Model 1 (M1)						Model 2 (M2)					
	Brzev (2007)		EERI (2011)		Transformation		Brzev (2007)		EERI (2011)		Transformation	
	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y
1	1.52	1.80	6.07	7.22	4.44	3.43	1.52	1.80	6.07	7.22	4.44	3.43
2	1.52	1.80	6.07	7.22	5.92	4.57	1.19	1.41	4.75	5.65	3.97	3.21
3	1.52	1.80	6.07	7.22	8.89	6.86	0.92	1.10	3.69	4.39	4.02	3.40
4	1.52	1.80	6.07	7.22	17.77	13.72	0.86	1.02	3.43	4.08	7.17	6.16
1	1.52	1.80	6.07	7.22	4.44	3.43	1.52	1.80	6.07	7.22	4.44	3.43

The WDI value is 4.84% for the 4-story building. Comparing to the three methods of WDI calculation, the WDI with the transformation method resulted in value closer to Mexican Regulation. It takes into account differences in material quality (concrete and brick), and its value meets the requirements also.

4.2. Displacement and Drift Ratio

Displacements in X and Y direction shown in figure 4 were calculated using the load's combination of dead, live, and earthquake loads ($D + L + E$). The maximum displacement that occurred at the top floor in the X direction was 1.42 mm, 1.56 mm and 1.52 for M1, M2, and M3, respectively, while for direction Y were of 1.9 mm, 2.1 mm and 2.0 mm. An intersection on the graph occurs due to the influence of the structure's weight.

The biggest drift ratio in the M1 model occurred on the 3rd floor with a value of 0.0159% while in the M2 and M3 models occurred on the 4th floor, which was 0.0164% and 0.0159% respectively. In Indonesia, there are no regulations yet regarding the confined masonry drift ratio, but the Chilean Code does. The drift ratio of 0.2% is allowed. The drift ratio of all three models is less than 0.2%; therefore, it satisfied the code.



Displacement for all models in the X direction

Displacement for all models in the X direction

Figure 4. Displacements of all models in X and Y direction.

4.3. Stresses on the Wall

Typical stress contours are obtained from the analysis for all three models. The compressive, tensile, and shear stresses of M1 are shown in figure 5 to figure 7.

The stress on the wall is smaller than the allowable where the greatest compressive stress occurs due to a combination of $1.2D + L - 0.3Ex - Ey$ of 0.418 MPa less than 3 MPa, or the ratio was of 0.14. The largest tensile stress occurs due to a combination of $1.2D + L - Ex - 0.3Ey$ of 0.313 MPa < 0.414 MPa with a ratio of 0.76. The largest shear stress occurs due to a combination of $1.2D + L - Ex - 0.3Ey$ of 0.247 MPa < 0.525 MPa ratio of 0.47.

For M2, the compressive stress and maximum shear stress that occur on the wall were smaller than the permissible stress, but the maximum tensile stress that occurs on the 4th-floor wall near the column exceeded the tensile stress. The largest compressive stress occurs due to a combination of $1.2D + L + 0.3Ex - Ey$ of 0.450 MPa < 3 MPa ratio of 0.15. The largest tensile stress occurs due to a combination of $1.2D + L - Ex - 0.3Ey$ of 0.526 MPa > 0.414 MPa ratio of 1.27. The largest shear stress occurs due to a combination of $1.2D + L - Ex + 0.3Ey$ of 0.246 MPa < 0.525 MPa ratio of 0.47.

For the M3 model, all stresses were less than the allowable ones. The largest compressive stress occurs due to a combination of $1.2D + L + 0.3Ex - Ey$ of 0.479 MPa < 3 MPa ratio of 0.16. The biggest tensile stress is due to a combination of $1.2D + L - Ex - 0.3Ey$ of 0.389 MPa < 0.414 MPa ratio of 0.94.

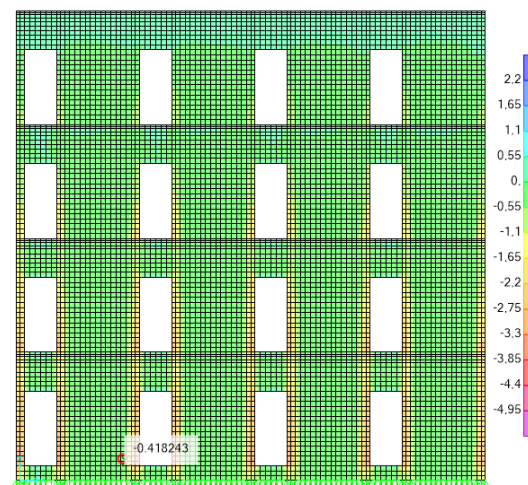


Figure 5. Maximum compressive stress in model M1 (MPa).

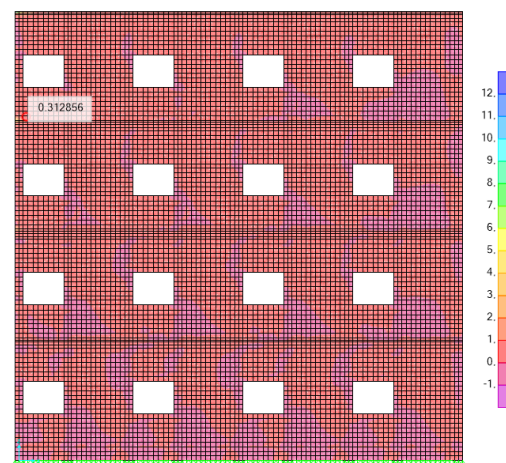


Figure 6. Maximum tensile stress in model M1 (MPa).

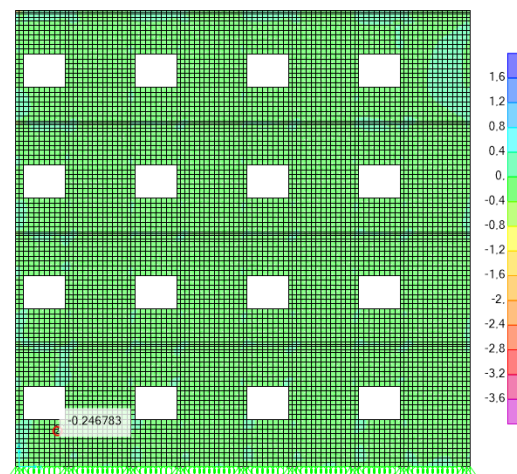


Figure 7. Maximum shear stress in model M1 (MPa).

The largest shear stress is due to a combination of $1.2D + L - Ex - 0.3Ey$ of $0.295 \text{ MPa} < 0.547 \text{ MPa}$ ratio of 0.54. From the WDI results, it can be seen that if the WDI value is smaller than the requirements, the compressive stress, tensile stress, and maximum shear stress of the wall will satisfy the allowable stresses. Similar results are also obtained wherewith WDI is smaller than the rules that meet the requirements for stiffness and stress [15]

Due to gravity and earthquake load, there is no tensile stress on the 1st floor for M1 in both directions. For M2, there is tensile stress of 0.016 MPa in the X direction and 0.014 MPa in the Y direction. For M3, there is no tensile stress in the Y direction, whereas there is tensile stress of 0.002 MPa occurs in X. On the 4th floor of M2, the stress ratio relative to M1 is 1.68, where the stress that exceeds the permitted stress. Between all models, it can be concluded that M1 and M3 only fulfill the stress and other design requirements.

4.4. Reinforcement in Concrete Columns and Beams

Based on the tensile stress results, the longitudinal reinforced bar is calculated for columns and beams. For shear reinforcement on the beam, it is calculated based on shear stress, while in the column, it is calculated based on the basic shear force. Reinforcements in columns and beams are presented in table 7.

Table 7. Reinforcement on concrete column and beam.

Reinforcement	M1		M3	
	Column	Beam	Column	Beam
Longitudinal	4D13	4D13	4D13	4D13
Transversal	ø8-200	ø8-200	ø8-200	ø8-200

5. Conclusion

Modeling of confined wall structures (CWS) was carried out using shell elements where wall thickness was varied. Model 1 (M1) with fixed wall thickness, Model 2 (M2) with thinning wall thickness upwards, and Model 3 (M3) as M2 but different dimensions were analyzed. Based on the results, it can be concluded as follows:

- CWS modeling uses shell elements capable of mimicking the displacement results in elastic parts.

- From various wall density index (WDI) calculations, the transformation method is closer because it takes into account differences in material quality (concrete and brick), and its value meets the requirements of the WDI according to Mexican Regulations.
- Based on the displacement results in the maximum drift ratio of M1, M2, and is 0.0159%, 0.0164%, and 0.0159% respectively. The drift ratio that occurs is less than 0.2% fulfill the Chile Regulation.
- The compressive stress, tensile stress, and shear stress that occur in the fixed thickness model (M1) and the model with a thinning thickness upwards (M3) still meet the permitted stress. Therefore, the CWS can be made with varying wall thicknesses.

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