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Seismic Risk Of Soft Story Residential Building Designed As Infilled Frames

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Abstract – This study was conducted to determine the seismic risk of a residential building with soft story considering infill wall in the analysis. Four models of 4 story dormitory building were analyzed to evaluate their performances. The first model was the actual building with infill wall at the upper levels and partially open at ground level (partial soft story - M1Pss). In the second model all walls in ground floor were removed (full soft story-M2Fss). A full infill wall at all levels (M3Non-ss) and an open frame model (M4OF) were also created to be compared to the soft story models. All models were loaded with gravity and quake load appropriate for east Bali region and pushover analysis were performed. Results show that the soft story mechanism occurs due to the absence of the infill wall at ground level (M1Pss and M2Fss). In model with distributed wall (M3Non-ss) and open frame model (M4OF) soft story mechanism was not detected. Accordingly, the infill wall should be considered in the analysis of multistory frame to avoid undetected soft story mechanism.

Keywords – Diagonal strut; Infilled frame; Pushover analysis; Seismic risk; Soft story

I. INTRODUCTION

In many countries including Indonesia, most of the low-rise residential buildings use brick walls as partition. Often time the wall infills the frame, forming an infilled frame structure instead of an open frame (OF). In such cases, the stiffness of the story with an infill wall will be significantly larger than that without infill. In many cases, the ground floor of these residential buildings is open for parking while the upper floor is full of infill walls, which results in a soft story structure due to discontinuity of the infill walls.

By definition, a soft story is a story with 70 percent less stiff than the story above it or 80 percent less lateral stiffness than the average of three stories above it. It also has an inter-story drift ratio of 130 percent greater than that of the story above it under design earthquake load [1]. The soft story occurs due to the existence of a weak level with much smaller lateral stiffness than the upper stories. Visually, a soft story is also defined as a structure with an open ground floor that has no walls or fewer walls than the stories above it.

The typical structure of low to medium-rise residential buildings in Indonesia consists of a reinforced concrete (RC) frame with a partition wall inside the frame that forms a new type of structure called the infilled frame (IF). The analysis of this type of structure is not yet widely known among building engineers and therefore, the infill wall is excluded during structural analysis and design. Accordingly, the soft story mechanism will be undetected.

Research shows that infill walls enhance the strength and rigidity of the frame subjected to lateral load through composite action between walls and frames. An experimental study [2] shows that infilled frames have higher strength and stiffness compared to the bare frame. The presence of infill walls increases the strength and stiffness of the structure [3][4][5]. Hence, when there is an open ground level in IF structure, it can cause a soft story mechanism [6][7][8][9]. As happened during Nepal's strong earthquakes in 2015, damaged structures are mostly caused by soft story failures [10]. The IF with an open ground story also produces higher shear forces on columns than open frame (OF) structure [11], this can cause ground floor's columns failure before that in the upper floors, leading to soft story failure.

Municipal Fire Station in San Pedro Sacatepéquez, San Marcos in Guatemala, almost collapsed due to the lower floor structure being weaker than the structure above it because of an unexpected interaction between the frame and the infill wall. In the 1995 Kobe earthquake, about 55,000 buildings were destroyed and most of them were caused by a soft story, especially the ground floor, which was weaker than the levels above, which caused soft story failure [12]. A 17-story building with the same condition collapsed due to a soft story in Tainan City, Taiwan, after being shaken by an earthquake with a magnitude of 6.4 in Kaohsiung [13]. Soft story failure could also be due to the short column effect. One of the triggers for short columns is the placement of partial infill walls. When laterally loaded, due to an earthquake, a shorter column will carry a greater load than a taller column [14].

Buildings in Bali, Indonesia, are usually built with a pitched roof with maximum height of 15 m. Figure 1 shows a typical low-rise dormitory building recently built in Denpasar and Bangli, Bali showing an open ground floor for parking. There are many more construction of this type such as city hotels that visually obvious of having soft story problems. Those structures fall into the category of the soft story because part of the ground floor is used for parking while all of the upper floors are used as rooms with infill walls. To study the risk of soft story failure during strong earthquakes, the partial soft story building mentioned above was analyzed using pushover analysis in SAP2000. As a comparison, the same analyses were performed on three different hypothetical modified structures, namely a fully soft story frame, a fully infilled frame, and an open frame.

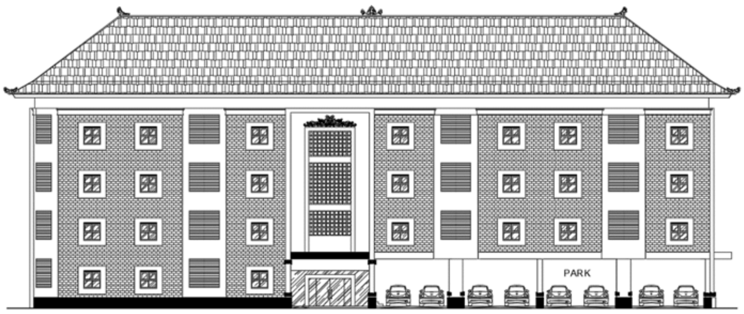


Fig. 1. Typical low-rise dormitory building showing partial soft story at ground floor

The aim of this study is to investigate the importance of including infill wall in the analysis and design of RC frame structure, especially when the wall is not well distributed along the height of the building. From the results of this simulation models a better understanding of the effect of infill wall on the performance of infilled frame structures subjected to strong quake can be obtained.

II. METHODS

To serve the purpose of this study, four models of 4 story dormitory building shown in Fig. 1 were analyzed to evaluate their performances. The first model was the actual building with infill wall at the upper levels and partially open at ground level (partial soft story - M1Pss). In the second model all walls in ground floor were removed (full soft story-M2Fss). A full infill wall at all levels (M3Non-ss) and an open frame model (M4OF) were also created to be compared to the soft story models. In addition to evaluating the performance of each model, modification to the structure at ground level was done by enlarging the size of columns in that area to prevent soft story mechanism.

A. Geometrical and Material Properties

The ground floor plan for M1Pss shown in Fig. 2 consists of partial infill walls from grid A to E. In M2Fss all the infill walls at ground floor were removed and M3Non-ss has full infill walls from grids A to I, grid 2, and 3. Figure 3 shows the second to fourth-floor plan for all the models except for M4OF. S1, S2, and S3 shown in Fig. 2 and 3 are the infill walls associated with

Strut 1, Strut 2, and Strut 3, respectively. The story height is 3.5 m for all levels. The distance between frames is 6 m in the longitudinal direction while in the transversal direction the bay is 1.85 m and 6 m. The slab thickness of 130 mm is used with a secondary beam in the longitudinal direction and the slab thickness for the roof is 100 mm. Grid H-H section for all models is shown in Figure 4.

The column size is 400/550 for all models. For the second and third floor, the beam size of 300/500 is used as exterior and interior beams in the x-direction, and 300/600 as an interior beam in the y-direction. In x-direction, the secondary beam is 250/500. The ring beam size is 250/400. For roof structure, steel profile of H200x200x8x12 is used for columns, WF200x100x5.5x8 for rafters, and CNP 150x50x20x3.2 for purlin. All dimensions are in mm. The column and beam sizes were the same for all the models.

Material properties were assigned using as-built structure materials. Concrete modulus of elasticity, E_c, is based on concrete compressive strength f'_c of 29.05 MPa. The infill wall elastic modulus, Em is 1635.5 MPa using a formula from [15]. Infill wall strength, f'm of 2.97 MPa [16] with 150 mm wall thickness. The roof structure uses a steel grade of 240 MPa. The compressive strength of the walls was lower compared with the similar brick prism tested by Foytong et al.[17].

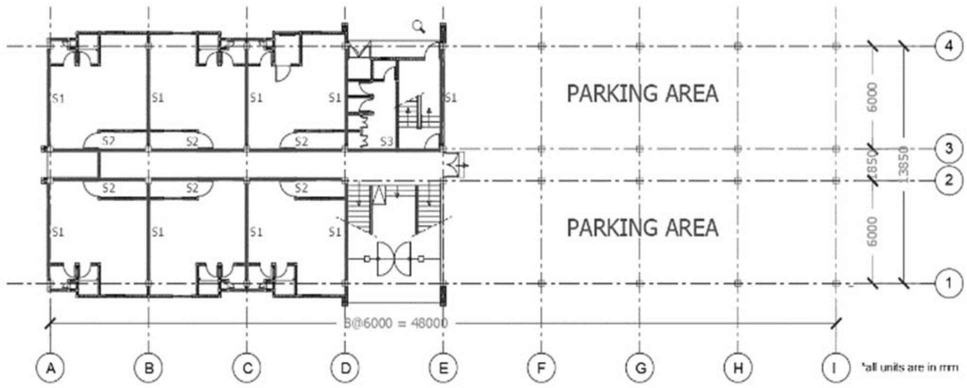


Fig. 2. Ground floor plan for M1Pss

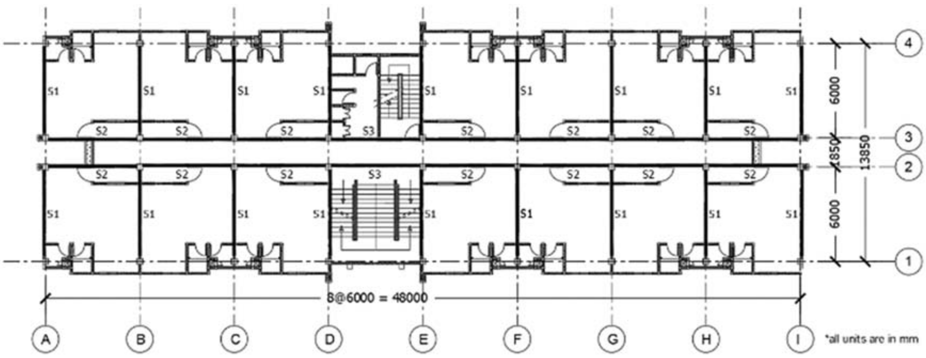


Fig. 3. Second to fourth floor plan for M1Pss

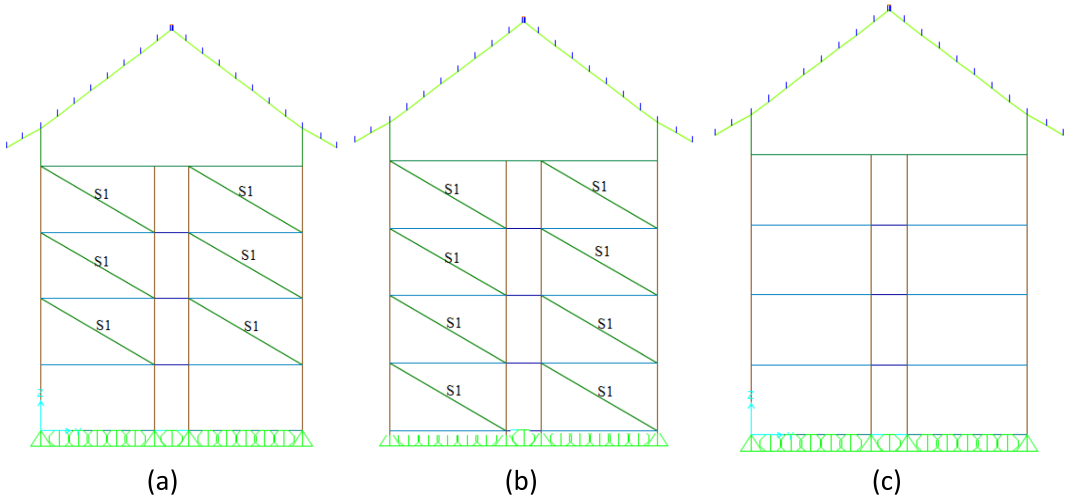


Fig. 4. Grid H-H section in (a) M4OF; (b) M3Non-ss; and (c) M1Pss & M2Fss

B. Infill Wall Modelling

Formula from Sukrawa and Budiwati [9] as shown in Equation 1 and Equation 2. The formula has a simpler form than the formula suggested by Federal Emergency Management Agency [15] and considered confinement around its opening, as it is widely known that confinement along its openings performs better under compression. An experimental result conducted by Sigmund and Penava [2] of infilled frames (IF) with wall openings, with and without confinement, shows that the confinement around the openings was capable of preserving the lateral strength, stiffness and ductility of the tested IF without confinement, as in the case of a solid IF. In practice, confinement along the opening uses a square practical reinforcement concrete beam and column as thick as the infill wall. The results for the strut width calculated with Equation 1 and 2 are shown in Table 1.

$$W_{sco} = \frac{d}{20\,tan\,\theta} fc'^{0.5} C \qquad (1)$$

$$C = 1.126r^2 - 2.212r + 1.0971 \qquad (2)$$

where Wsco is the diagonal strut width (mm), d is the length of the diagonal strut (mm), Ɵ is the angle of the diagonal strut, f'c is the strength of the concrete frame (MPa), C is a non-dimensional correction factor for confined opening, which is calculated by Equation (2). The value of C is less or equal to 1. The r is the ratio between the opening area of the wall and the full area of the wall. The detail for the variables used in Equation 1 is shown in Figure 5.

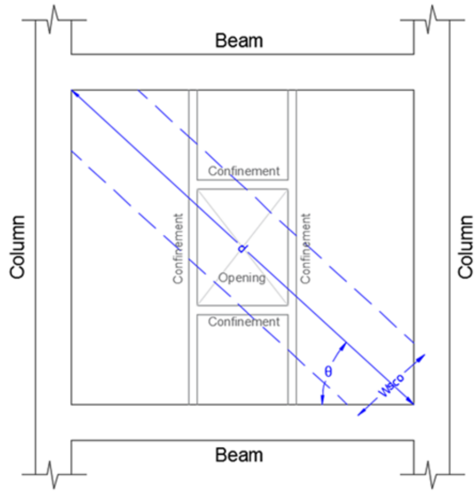


Fig. 5. Example of an infill wall with formula variables

TABLE I. WIDTH OF DIAGONAL STRUT

Type	d (mm)	tan θ	Opening Area (mm^2)	R (%)	C	W_{sco} (mm)
S1	6946	0.58	0		1	3209
S2	5981	0.72	0		1	2234
S3	6946	0.58	10,500,000	50 %	0.27	875
S4	6946	0.58	15,100,000	72 %	0.09	285
S5	6946	0.58	5,400,000	26 %	0.60	1934
S6	6946	0.58	9,000,000	43 %	0.36	1142

C. Modelling and Loads

The structure was modelled using SAP2000. Beams, columns, and diagonal strut (infill wall) were modelled as frame element and the floor slab was modeled using shell element. The dead load for 2nd–4th floor is 1.42 KN/m2 and 1.19 KN/m2 for roof slab. Dead load for the wall was inputted using distributed and joint load at each position whose location corresponds to the wall position. The value for a lightweight brick load was 100 kg/m2. For dormitory building, according to SNI 1727:2013, the live load for dormitory and corridor was 1.92 KN/m2. The roof live load was 0.2 KN/m2.

Earthquake load was calculated using the auto lateral load feature in SAP2000 based on IBC 2009. There were several parameters related to this building earthquake data, such as occupancy category II, seismic importance factor 1, seismic design category D, site class D, mapped spectral response acceleration Ss was 0.983 g and S1 was 0.354 g, the seismic-force-resisting system was an infilled-frame structure with response modification coefficient (R) value of 6 [9], over strength system factor (Ωo) of 3, and deflection amplification factor (Cd) of 3,5 [9].

Soft story evaluation was analyzed by two methods, inter-story drift ratio and pushover analysis. The performance level of the structure was also evaluated using the pushover analysis method based on ATC-40. The steps for the pushover analysis include defining the hinge properties using the auto hinge properties of ASCE 41-13 available in SAP2000 [18].

After modelling and analysis were done, the stress of walls was also checked. Acceptable shear stress is calculated by a formula from Agarwal and Shrikhande (2006) as shown in Equation 3, while acceptable axial stress must be lower than the value of lightweight block compressive strength, which is 2.97 MPa

$$\tau = \tau_0 + \mu f_n \tag{3}$$

where τ is the ultimate shear strength of the brickwork (N/mm2), τ_0 is cohesion or bond strength between the mortar to brick (N/mm2), f_n is normal compressive stress (N/mm2), and μ is coefficient of internal friction of brickwork. The μ varies from 0.2 to 0.84 and τ_0 varies from 0.2 to 0.4 N/mm2. To increase the safety for this analysis, a minimum value is taken at 0.2 for μ and 0.2 N/mm2 for τ0.

The design of reinforcement for all models was carried out based on Indonesian code which is the same as ACI code [19]. The requirement for special moment frame was used because of the seismic design category D.

D. Soft Story Evaluation

The structure evaluation related to the soft story mechanism is evaluated using two methods, which are inter-story drift ratio analysis and pushover analysis through the forming mechanism of plastic hinges. Inter-story drift analysis uses the results of lateral displacement obtained from the results of a linear analysis on SAP2000. The displacement value is then multiplied with the lateral deflection magnification factor (Cd), which is 3.5 for the infill wall structure system and then divided by the earthquake importance factor (I), which is 1. The structure is categorized into a soft story structure if its inter-story drift ratio is 30 per cent greater than the story above [1]. In pushover analysis, the forming mechanism of plastic hinges is observed to evaluate the soft story occurring in the structure. When the plastic hinge in the column is first formed on the ground floor, it means that the ground floor fails before the floor above it. If the soft story mechanism occurs, the model will be modified by enlarging the column dimension on the level where the soft story mechanism occurs.

III. Results and Discussion

E. Displacement and Period

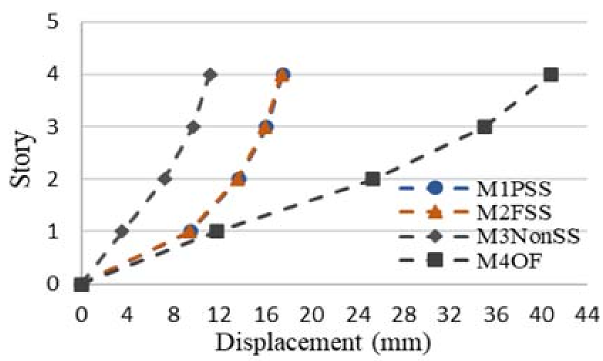
Analyses of all models show that the existence of infill walls in the model change the behavior of the frame significantly. Figure 6 (top) shows the average of lateral displacement in the transversal direction at each floor of all models. The average lateral displacements in the longitudinal direction are also shown in Figure 6 (bottom) showing the same behavior with the transversal direction.

Figure 6 (left) shows the top floor displacement of the M4OF model, which is 2.7 times larger than those of infill walls models. This shows that infill walls could increase the lateral stiffness of the structure. Lateral displacement of the ground floor of M1Pss, M2Fss, and M4OF models are 9.5 mm, 9.4 mm, and 11.8 mm, respectively, while the displacement of M3Non-ss, which is a full infill frame model, is only 3.6 mm, about 2.6 to 3.2 times smaller than the lateral displacement of other models.

The average lateral displacements in the longitudinal direction are shown in Figure 6 (right), it has the same behavior with the transversal direction generally. The top floor displacement of the M4OF model is 1.7 times larger than those models with infill walls. At the ground floor, M1Pss, M2Fss and M4OF with an open ground floor show lateral displacement of 12.7 mm, 14.6 mm, and 18.1 mm, while the displacement of M3Non-ss, which is a full infill frame, is 10.2 mm, about 1.2 to 1.7 times smaller than the lateral displacement of other models.

It shows that models with an open ground floor have a small stiffness level and the presence of an infill wall at the upper level increased the level's stiffness significantly. M3Non-ss lateral displacement shows that the stiffness of the frame increases at all levels, while in M1Pss and M2Fss without infill wall at ground level, the stiffness on the ground level is smaller than that on the upper levels. This means that discontinuity of infill wall at ground level reduces the stiffness at that level, which leads to soft story mechanism.

Referring to a modal analysis by SAP2000, IF structures namely M1Pss, M2Fss, and M3Non-ss, have an average of 15 per cent smaller period than the open frame (M4OF) structure. This means that the IF structure is much stiffer than OF structure because the existence of the infill wall contributed to withstand loads.



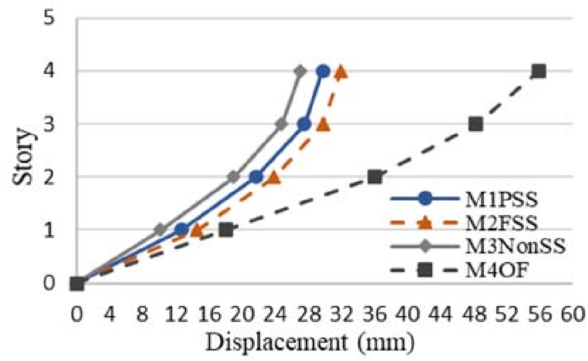


Fig. 6. Lateral displacement in the transversal direction (left) and the longitudinal direction (right)

F. Stress of Walls

Stresses on the walls in the strut models were evaluated manually using the axial force and area of the diagonal strut that produced normal compressive stress along the diagonal while the horizontal part of the axial force caused shear stress. The calculations of the stresses are shown in Table 2.

TABLE II. COMPRESSIVE AND SHEAR STRESS OF WALLS

Model	P (N)	θ	Compressive Stress			Shear Stress		
			P sin θ (N)	*Compressive Section Area (mm2)*	*f_V (MPa)*	*P cos θ (N)*	*Shear Section area (mm^2)*	*f_H (MPa)*
M1Pss	31910	30	15996	81165	0.20	27611	49485	0.56
M2Fss	25170	30	12617	81165	0.16	67797	151950	0.45
M3Non-ss	26596	30	13332	81165	0.16	72923	151950	0.48

The highest normal compressive stress in each model was 0.20, 0.16, and 0.16 MPa for M1Pss, M2Fss, and M3Non-ss, respectively. All three stresses were less than the compressive strength of lightweight brick of 2.97 MPa. Therefore, the compressive strength of the lightweight brick wall was not exceeded.

The maximum shear stress on the walls were 0.56, 0.45 and 0.48 MPa for M1Pss, M2Fss, and M3Non-ss, respectively. Compared to the shear strength of 0.79 for lightweight brick that was calculated using Equation (3), the wall didn't show any shear cracks under the design earthquake load.

The stress on walls gradually increases as the level gets lower. If the same qualities of materials were used for all walls and a stronger earthquake happened, the walls on the bottom floor will fail before those on the upper level. In this case, the soft story mechanism might occur because of the failure of infill walls on the ground floor. To prevent this, walls on the lower level need to be stronger. This can be achieved by using thicker or stronger material for walls on the lower floor level.

G. Soft Story Evaluation (Inter-story Drift Ratio)

The inter-story drifts of all models in the transversal and longitudinal direction are shown in Figure 7. It can be seen that M1Pss and M2Fss which have open ground floor have larger first story drifts than that in the upper story. The differences were more than 50% that exceed the limit of 30%. For the non-soft story model, M3Non-ss the drift for the first story and upper stories are not much different. This means that the absence of infilled wall on the ground floor reduce the stiffness and hence, the drift of the first floor become much higher than that of the upper floor. For the M4OF model, the inter story drift of the first story was less than that of the second story. This means that when infill walls are not considered in the analysis such as in M4OF, the soft story mechanism could not be detected.

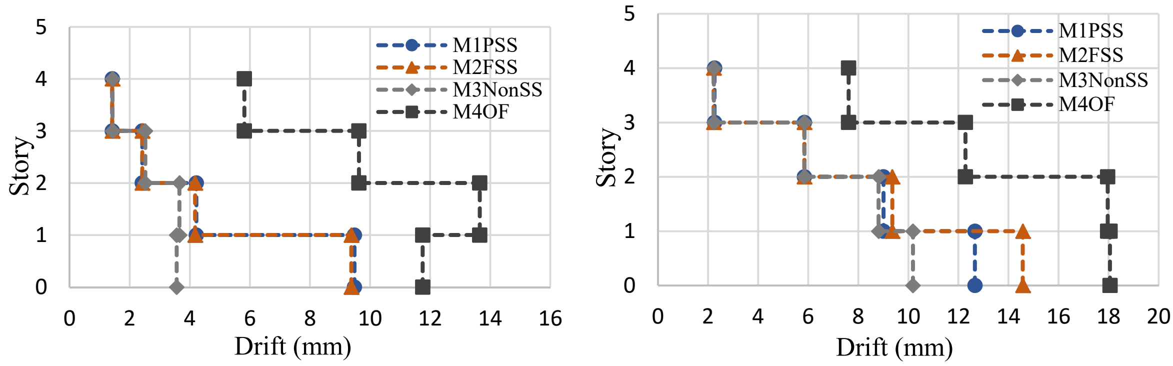


Fig. 7. Inter-story drift: transversal (left) and longitudinal direction (right)\

H. Design Result

The reinforcement results of the four models are shown in Table 3. The column reinforcements were all the same which is minimum reinforcement required by the code. The beam reinforcement however, varies from model to model. The M3Non-ss model require the smallest rebar area because of the full infill wall contribution in resisting lateral loads. Meanwhile, the open frame model requires the largest rebar area. The simulation models showed that the presence of infill wall in RC frame reduce the reinforcement in the frame.

TABLE III. REINFORCEMENT REQUIREMENT

	Reinforcement (mm^2)			
	M1Pss	***M2Fss***	***M3Non-ss***	***M4OF***
Column*	2200	2200	2200	2200
Beam	456	516	445	570

I. Pushover Analysis Result

The plastic hinges obtained from a pushover analysis are used to evaluate the soft story mechanism. Pushover curves for all models are shown in Figure 8. Plastic hinges formation in M1Pss, M2Fss, M3Non-ss, and M4OF are shown in Figure 9 and 10 respectively, while for the modified model, by enlarging the column size, can be seen in Figure 13.

Pushover analysis results are shown in Figure 8. IF models (M1Pss, M2Fss, and M3Non-ss) have a higher base shear than models without infill walls or open-frame model (M4OF). On its performance point, the average base shear for all IF models were 1.8 times larger than that of OF model. Figure 8 also shows that M4OF has a larger displacement than all IF models which means that the lateral strength and stiffness of the frame were increased due to the presence of infill walls.

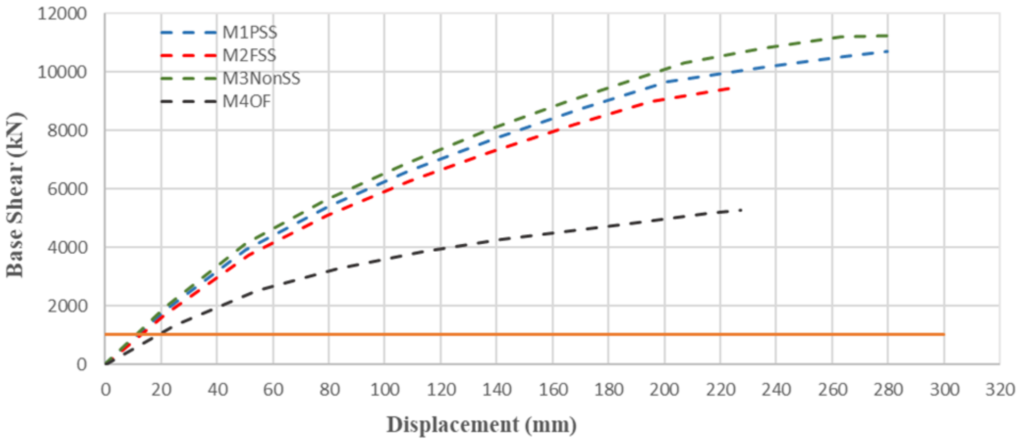
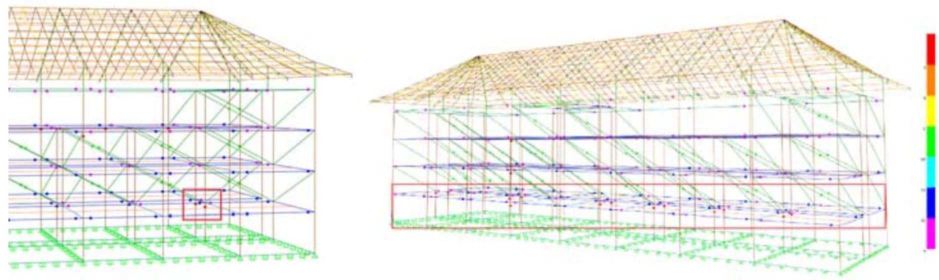


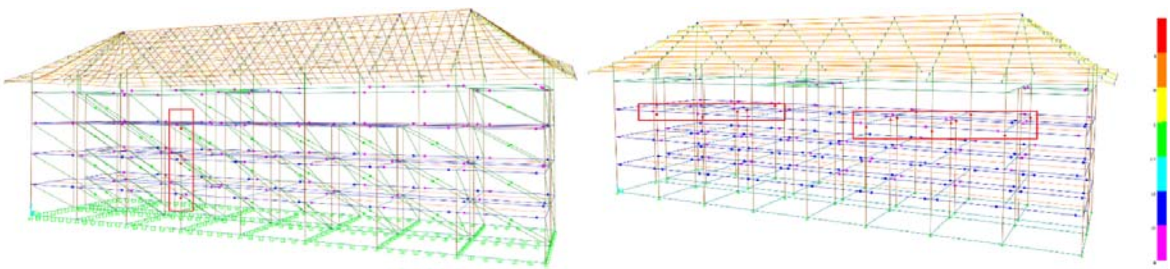
Fig. 8. Pushover curves for all models

Based on the results of the pushover analysis, for the M1Pss model, the performance point was obtained in step 2 with value (V; d) of (4459 KN; 61 mm) and the structure performance level is at immediate occupancy (IO). Also shown in Figure 8 the design shear value of 1025 KN (the horizontal line). When compared with the basic shear force at the performance point, it shows that the structure could withstand earthquake loads 4.3 times greater than the design earthquake load.



(a) (b)

Fig. 9. Plastic hinges formation at performance point in soft story models (a) M1Pss and (b) M2Fss



(a) (b)

Fig. 10. Plastic hinges formation at performance point in Non-soft story models (a) M2FNonSS and (b) M4OF

For the M1Pss model, the first plastic hinge formed on the wall (diagonal strut) at B to IO condition, then plastic hinges continued to form on the beams and then the columns. At its performance point, 47 plastic hinges formed in B to IO condition (on beams), 26 plastic hinges in CP to C condition formed on the wall as shown in Figure 9 (a). The plastic hinge on the column was firstly formed on the ground floor's column (parking area) and then on the columns of the upper floors at step 5 with beyond E condition. This means that if subjected to strong earthquake, the structure will fail due to soft story because of discontinuity of the infill wall.

Similar to that of M1Pss model, the M2Fss model shown in Figure 9 (b), the first plastic hinges were formed on the walls (diagonal strut) at B to IO condition, then continued on the beams and the columns. At its performance point, 47 plastic hinges formed in B to IO condition (on beams), 19 plastic hinges in CP to C condition formed on the wall. In step 4, the first plastic hinges on columns were formed on 13 columns at ground floor. This also means that the model failed due to soft story.

For the non-soft story models, the performance point of M3Non-ss was obtained in step 2 with value (V; d) of (4565 KN; 59 mm) and performance level of immediate occupancy (IO). The structure could withstand earthquake loads as much as 4.5 times greater than the design earthquake load. The first plastic hinge formed on the wall (diagonal strut) at B to IO condition, then continued on the beams and then the columns. At its performance point, 40 plastic hinges formed in B to IO condition (on beams), five plastic hinges in IO to LS condition, one plastic hinge in LS to CP condition, and 35 plastic hinges in CP to C condition formed on the wall (shown in Figure 10.a). Interestingly enough, the first plastic hinge did not form in the ground floor column. This proves that, when the walls are continuously distributed, the soft story mechanism does not occur.

In the M4OF model, the performance point is obtained in step 3 with value (V; d) of (2884 KN; 68 mm) with performance level of life safety (LS). The structure can withstand earthquake load 2.8 times greater than the design earthquake load. The first plastic hinge is formed on beams and continued to the columns. At its performance point, 85 plastic hinges at B to IO and 63 hinges at IO to LS condition formed on beams. The first plastic hinge formed in the third floor with 16 plastic hinges at beyond E condition. This proves that, when the infill wall is not considered as a structural element, the actual behavior of the structure will not be known. Meanwhile, when the wall is included in the analysis such as in M1Pss model, soft story mechanism was confirmed if the structure was subjected to strong earthquake.

J. Modified Structure and Evaluation

To prevent soft story failure under strong quake, the soft story model of M1Pss was modified by enlarging the column in the parking area and then push over analysis was performed. The dimension of the ground floor's column of the M1Pss model was enlarged from 400/550 to 500x1100. The inter-story drift of the modified model show that no soft story was detected. The plastic hinge formation obtained from pushover analysis also show that the plastic hinges were not formed in the enlarged columns as shown in Figure 11. These results show that to prevent soft story failure of RC structure with poor wall distribution the columns size in that area should be enlarged.

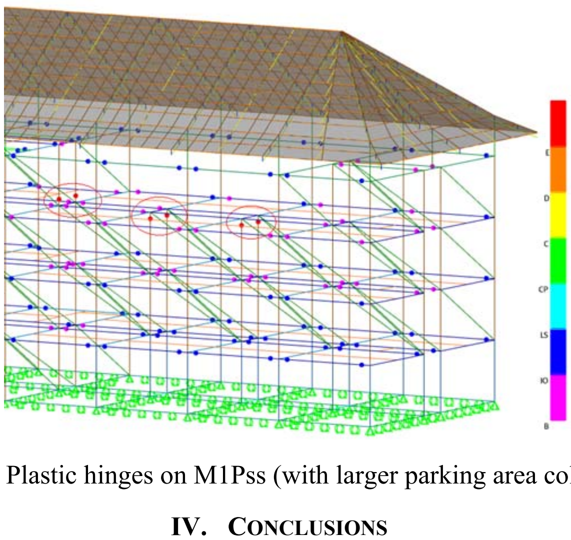


Fig. 11. Plastic hinges on M1Pss (with larger parking area columns)

IV. Conclusions

From the analysis results of simulation models of 4 story infilled RC frame with soft story at ground floor, the following conclusion can be drawn.

a. The infilled frame (IF) models are significantly stiffer and stronger than the open frame (OF) model, regardless of the wall distribution. Accordingly, OF model require more reinforcement than that of IF models.

b. The soft story mechanism was detected in IF models with partial or full soft story, but not detected in IF with no soft story and OF models. Therefore, the infill walls should be included in the analysis of RC frame to prevent the unexpected soft story failure, especially when the wall are not well distributed.

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