SEISMIC RESPONSES OF RC FRAME WITH DIFFERENT ARRANGEMENT OF MASONRY INFILL WALL

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Abstract: This study presents the suitability of using macro model (strut model) for analyzing the seismic responses of single-story single-span reinforced concrete frames having different arrangement of masonry infill wall with openings by comparing its results with those using micro model (wall-element model). From the result, the infill masonry wall increases the stiffness of RC frame structure. Meanwhile, the diagonal strut model will give smaller natural frequencies than wall-element model. When the part of the wall opening causes the wall to have no contact with a column, short column effect will be introduced in the column. Wall-element model can predict better the short column effect than the strut model. Although under static lateral load replacing masonry infill wall by diagonal strut was considered to be suitable for computing the response structure behaviour for the case without any opening in infill wall, but it is not the case for the dynamic analysis.

Keywords: masonry wall, diagonal compression strut, seismic response, natural frequency, short column effect

The shaking of strong earthquakes usually occurs for just tens of seconds only, but it can destroy or damage a lot of kinds of existing structures and infrastructures without sufficient earthquake-resistant design such as buildings, bridges, highways, and others. Therefore the structures need to be designed to resist earthquakes and remains good and safe conditions after the earthquakes.

For functional reasons, infill walls are used in reinforced concrete building and masonry is a material commonly used for such infill walls. In design and analysis, usually masonry infill walls are not considered as structural elements and their influences on the structural responses are ignored to avoid complicated calculations and to simplify analyses. Previous research has indicated that the use of masonry infill walls on reinforced concrete building will: (1) change significantly the seismic responses of the building during earthquakes, (2) cause the reinforced concrete building to have larger stiffness and strength than the building without masonry infill walls, and (3) increase self-weight of the building. However, during earthquakes the real situation is that the masonry infill walls will

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also resist lateral forces. Neglecting the presence of masonry infill wall in the analysis is not appropriate since it cannot reflect the real seismic responses of the building. Thus, it is imperative that the contribution of masonry infill walls on the seismic responses of the reinforced concrete building be investigated.

Through years a wide variety of analytical techniques have been proposed to evaluate contributions of the stiffness and strength of masonry infill walls to a reinforced concrete building. Generally these modelling techniques can be classified as macro model and micro model.

The concept of equivalent diagonal strut to model infill wall was initially introduced by Polyakov (1960). Based on observation of the infill boundary separation, he suggested that the infilled frame system is equivalent to a braced frame with a compression diagonal strut replacing the infill wall. Holmes (1961) presented formula for a diagonal strut for the first time. He proposed the width of equivalent strut to be one third of the diagonal length from his experimental study on a single-storey single-bay infilled structure under in-plane loads.

Smith and Carter (1968) observed that the equivalent diagonal strut has many simplifications and some modifications must be done on its equivalent width. He assumed that the distribution of the interactional forces between frame and infill walls is triangular. Based on the interaction length between infill wall and frame, other proposals were introduced by Mainstone (1971). Klinger and Bertero (1978) provided the first diagonal member with cyclic behavior which was able to consider the stiffness dimming behavior through the modelling procedure. Alternative proposals of non-linear behavior of non-integral infilled frames were given Liaw and Kwan (1984). And more recently equivalent diagonal strut width equations in seismic design of RC and masonry buildings proposed by Paulay and Priestley (1992). Table 1 summarizes different relations for the effective width of equivalent diagonal compression strut as assumed to replace masonry infill walls.

For the micro model, a masonry infill wall is modelled as wall element. The factors involved in the micro model are (1) length, height and width of the brick, (2) Young's modulus and Poisson's ratio of the brick material, (3) Young's modulus and Poisson's ratio of the mortar in the head and bed joints and (4) thickness of the head and bed mortar joints. It is considered to be more realistic but complicated in the analysis.

Achyutha, et.al. (1985) investigated the elastic behaviour of a single-storey masonry-infilled frame which had opening. The interface conditions such as slip, separation and frictional loss at the contact surface were achie ved by adjusting the axial, shear and tension force in the link element. The behaviour of masonry-infilled frame under an in-plane load was studied by Dhanasekar and Page (1986). The results from biaxial tests on half scale solid brick masonry were used to develop a material model for brick and the mortar joints which were then used to construct non-linear finite element model.

Haddad (1991) conducted study assess the effects cracking and separation between the frame and infill of an infilled frame structure. The model considered the crack size and location, relative stiffness and contact length. It was found that the bending and deflection decrease with the increase in infill frame relative stiffness. The cases with and without a perfect contact between the infill wall and the reinforced concrete frame was studied by Combescure, et.al. (1995) on a single-bay single-storey frame. It was reported, under unilateral contact condition (frictionless), the forces between the frame and fill panel are transferred through a compression corners at the ends of diagonal strut.

For the macro model, a masonry infill wall is modelled as equivalent diagonal compression struts through the observation and analysis of the experimental results. In the analysis the reinforced concrete building is treated as a braced frame structure with diagonal compression strut replacing masonry infill wall. It should be noted that the macro model is developed for the full masonry infill wall.

Pradhan (2012) studies the width of equivalent strut for partial masonry infilled on the reinforced concrete frames in static loading. The study was done to identify the shear force values at part of column when infilled masonry wall terminated through analytical formula. Rathi and Pajgade (2012) studies of masonry infilled reinforced concrete frame with and without opening. In analytical modelling, four models were considered: pure frame, fully infilled frame, infilled frame with center opening, and infilled frame with corner opening.

Diware and Saoji (2012) performed seismic assessment of symmetrical reinforced concrete structure with brick masonry infill. In this study, the reinforced concrete frame with brick masonry infill for different configuration of infill walls in plane were studied to observe the influences on the seismic response of the frame. Samoila (2012) conducted the analyses for the reinforced concrete frame single-story single-span reinforced concrete frame with masonry infill using macro model and micro model. For macro model infill wall was modelled as equivalent strut method, while for micro model the infill wall micro modelling was modelled as shell element. The analyses of masonry infilled concrete frame were carried out by modelling masonry infill through three main modelling techniques: finite element model, single-strut model, and three-strut model.

However in reality, usually infill wall is not fully installed on the RC frame to meet functional requirement such as door and window openings. To simplify the analysis, the macro model is frequently used for such a situation which has to be justified. Thus, through the numerical simulations using software Midas/GEN, objective of this study is to investigate the suitability of using macro model for analyzing the seismic responses of single-story RC frames having masonry infill wall with openings by comparing its results with those using micro models.

Table 1. Different Equivalent Diagonal Strut Width Formula

Researchers	Effective Width (b_w)	λh
Holmes (1961)	$b_w=[0.33]d_w$	-
Mainstone (1971)	$b_w=0.16(\lambda h)^{-0.3}d_w$	5
Klinger and Bertero (1978)	$b_w=0.18(\lambda h)^{-0.4}d_w$	5
Liauw and Kwan (1984)	$b_w=0.95h_w\cos\theta(\lambda h)^{-0.5}$	5
Paulay and Priestly (1992)	$b_w=[0.25]d_w$	-

(Source: Tabeshpour, et.al. 2012)

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Two methods used in this study that are static method and dynamic method. For the static method, the model used to verify the program is shown in Figure 1. RC frame was assumed fixed at bottom. Geometrical parameters of frame members can be seen in Table 2. The properties of the materials can be seen in Table 3. The load used was lateral load where load acting concentrated at the beam-column joint on left side of the frame as 164 kN. Three kinds of model were considered: full wall model, single strut mo-

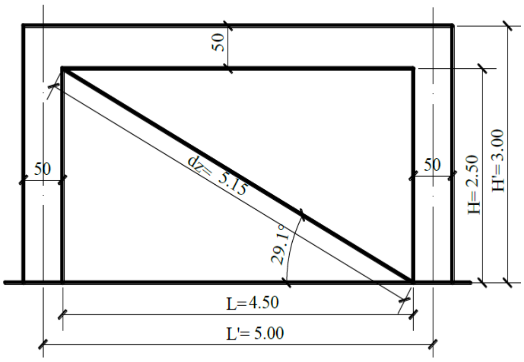


Figure 1. Reinforced Concrete Frame Model for Verification

del, and three struts model as shown in Figure 2. Model 1 has full infill masonry wall with 25 mesh elements in vertical and 15 mesh elements in horizontal, where masonry wall is modelled using plate element. For Model 2 the infill wall

Table 2. Geometrical Parameters of Frame Members

Frame Element	Transverse Section Dimensions [m]	Transverse Section Area [m²]	Moment of Inertia [m⁴]
Beam	$B_g x h_g$= 0.50x0.50	A_g= 0.13	I_g= 10.4x10^{-3}
Column	$B_s x h_s$= 0.50x0.50	A_s= 0.25	I_s= 2.60x10^{-3}

is replaced by a single diagonal compression strut. The equivalent diagonal compression strut width is 1.29 m, calculated based on Paulay and Priestley formula. Model 3 has three diagonal compression

Table 3. Properties of Materials

Materials	Modulus of Elasticity [kN/m²]	Poisson Coefficient
Concrete C20/25	Eb=30x10^6	0.20
Masonry	Ez=4.50x10^6	0.19

struts to represent the infill masonry wall. The width of central diagonal compression strut was taken 0.65 m, which is half the strut width in Model 2 and the width of eccentric struts is half of the central strut width that is 0.32 m. The eccentric struts were connected to the frame from beam-column joint at a distance of *lc*, which is the length of contact between infill and frame member element, suggested in the literature as shown in Equation.

$$l_c = \frac{\pi}{2}\sqrt[4]{\frac{E_b I_s H}{E_z t \sin 2\theta}} = 1.055m$$

The each model in this study is denoted in the form as A-B-C where A is the height of wall, B the width of wall and C the type of model. The model denoted as 0.75 H-0.50 L-S indicates that the height and width of infill wall are 0.75 H and 0.50 L, respectively, with the strut being used to model the wall. It will also be referred to as strut model in the discussion. The model denoted as H-L-W means that the height and width of infill wall are H and L, respectively, with the wall element being used to model the

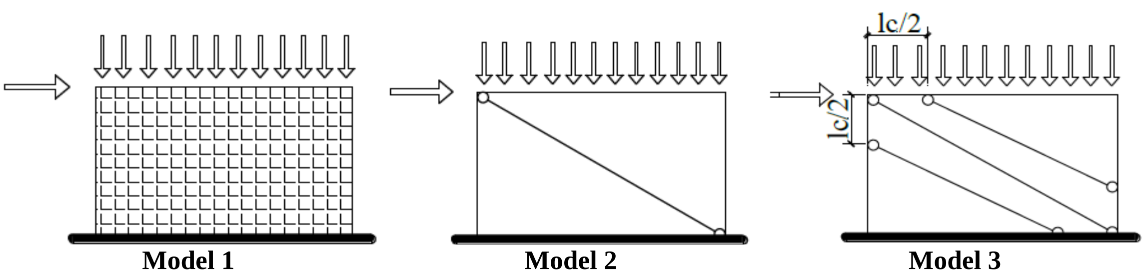
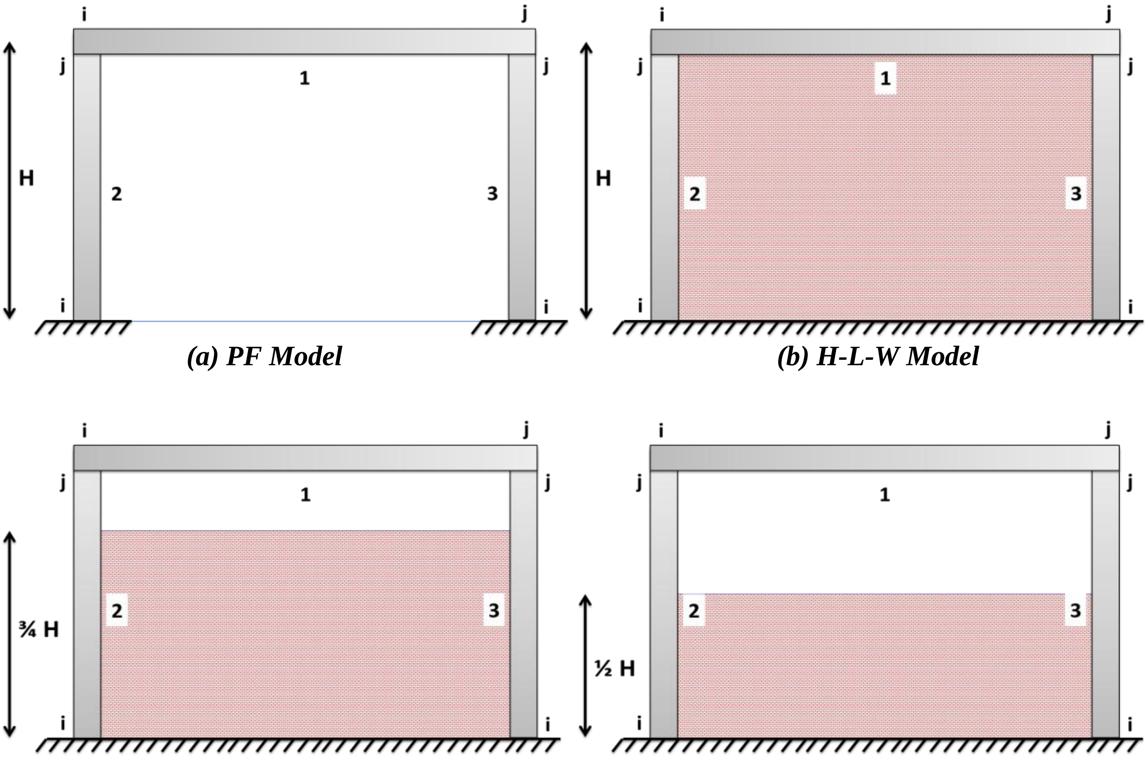


Figure 2. Three Models for Verification in Static Loading
(Source: Kaushik, et.al. 2008)

wall. It will also be referred to as wall-element model in the discussion. For the pure frame, it is denoted as PF.

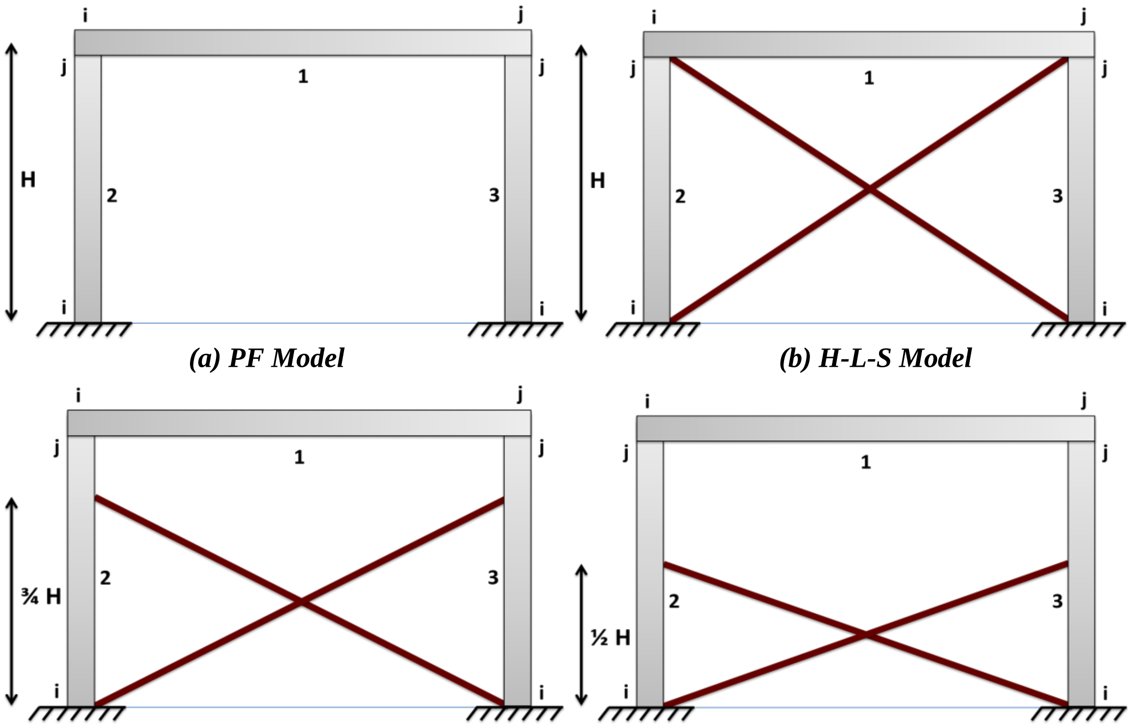
To investigate the effect of infill wall height on the suitability of using equivalent strut model for masonry infill



(a) PF Model *(b) H-L-W Model*

(c) 0.75 H-L-W Model *(d) 0.50 H-L-W Model*

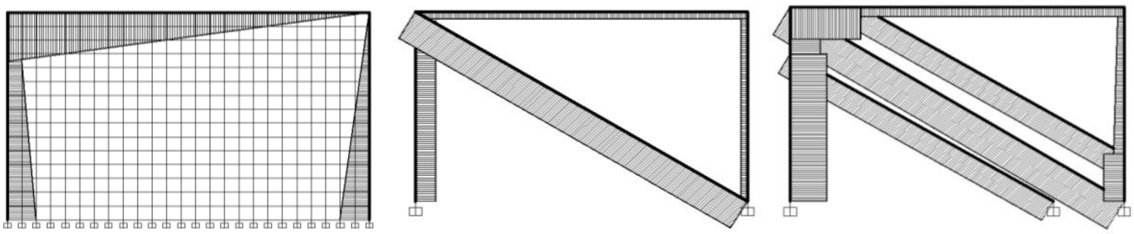
Figure 3. Models for Studying the Effect of Infill Height with Wall-Element Model



(a) PF Model *(b) H-L-S Model*

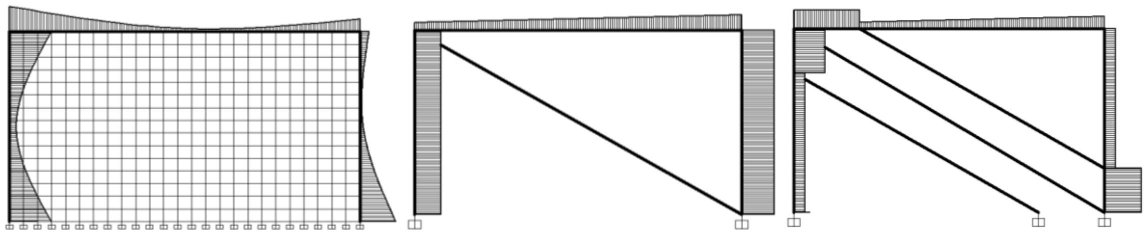
(c) 0.75 H-L-S Model *(d) 0.50 H-L-S Model*

Figure 4. Models for Studying the Effect of Infill Height with Strut Model



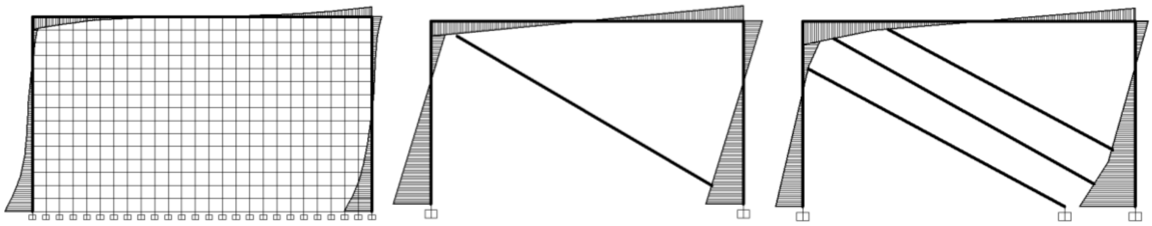
Model 1 **Model 2** **Model 3**

Figure 5(a). Diagrams of Distribution of Axial Force by MIDAS/Gen



Model 1 **Model 2** **Model 3**

Figure 5(b). Diagrams of Distribution of Shear Force by MIDAS/Gen



Model 1 **Model 2** **Model 3**

Figure 5(c). Diagrams of Distribution of Bending Moment by MIDAS/Gen

wall to predict seismic responses of reinforced concrete frame, Figure 3 and Figure 4 show the models analyzed. As shown in the models using wall element which are denoted as PF, 0.50 H-L-W, 0.75 H-L-W and H-L-W. While the models using equivalent strut which are PF, 0.50 H-L-S, 0.75 H-L-S and H-L-S. Beam is labelled as beam (1), the left column labelled as column (2) and the right column labelled as column (3).

RESULT

The results will be presented and discussed in this study are verification of static and dynamic method, natural frequency and internal forces including axial force, shear force, and bending moment. Natural frequencies will be compared between wall-element model and strut model in the first five modes. While the internal forces presented are the maximum ones at the ends of each beam and column element and the distributions of maximum shear force along each beam and column element.

For the verification of static case, the result of internal forces was done by Samolia (2012) using SAP2000 program which verified by MIDAS/GEN program. Figure 5(a), Figure 5(b) and Figure 5(c) show the comparison of distribution of axial forces, shear forces, and bending moments obtained by MIDAS/Gen. For the dynamic case, the comparison of natural frequencies of first five modes shown in Figure 6. the maximum of bending moment used to determine the appropriate mesh size. Figure 7 depicts the maximum bending moment both ends of frame elements.

Shown in the Figure 8 are the natural frequencies of the first five modes for all the models. The thin lines are the natural frequencies of wall-element model, the thick lines are the natural frequencies of strut element model, and the dash lines are natural frequencies of pure frame model in the first five modes respectively.

Figure 9 shows the axial forces at both node i and node j of beam (1), column (2) and column (3) using the wall-element model and strut model.

Figure 10 shows the shear forces at both node i and node j of beam (1), column (2) and column (3) using the wall-element model and strut model. Shown in Figure 11 and Figure 12 are the distributions of shear force along frame element using the wall-element model and strut model with the variation of infill height respectively.

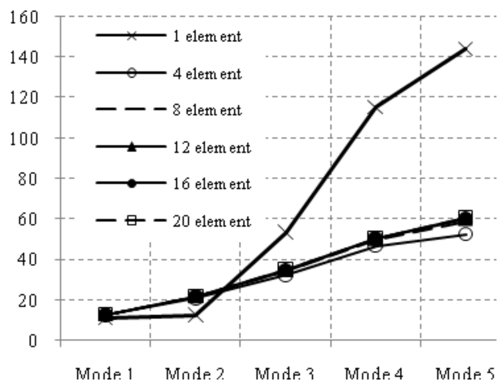


Figure 6. Comparison of Natural Frequencies of First Five Modes

Figure 13 shows the bending moment at both node i and node j of of beam (1), column (2) and column (3) using the wall-element model and strut model.

DISCUSSION

Samoila (2012) used SAP2000 program to analyze all the models and presented the computed axial forces, shear forces, and bending moment in beam element and column element. This program used to verify the methods of MIDAS/ Gen program. From Figure 5(a), Figure 5(b) and Figure 5(c) Generally, the result show the similar trend of distribution of axial forces, shear forces, and bending moments.

As shown in Figure 6, the comparison of natural frequencies of first five modes. When the beam element is discretized into 8 elements or more, the computed natural frequencies of first five modes are the same. This result also indicates that to get accurate natural frequencies of higher modes, the size of element must become smaller. Figure 7 depicts the maximum bending moment both ends of frame elements. To have convergent values the frame element the frame element must be at least discretized into 12 elements.

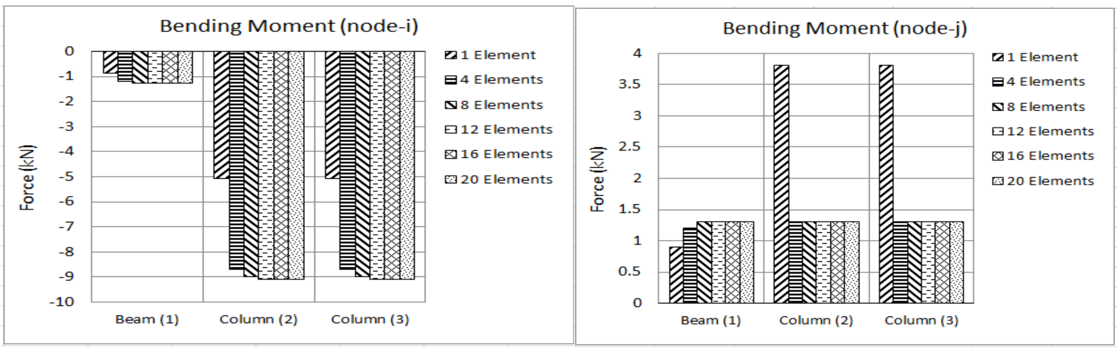


Figure 7. Comparison of Maximum Bending Moment with JMA Kobe Earthquake

From the figure 8 natural frequencies of all the models, it can be seen that infill masonry wall will increase the stiffness of RC frame structure which were also found in many previous studies, as compared with PF (Sofianto, 2014). On the other hand, the strut model will give the smaller natural frequencies. This may indicates the strut model may not be able to predict the behaviour of frame before the wall fails.

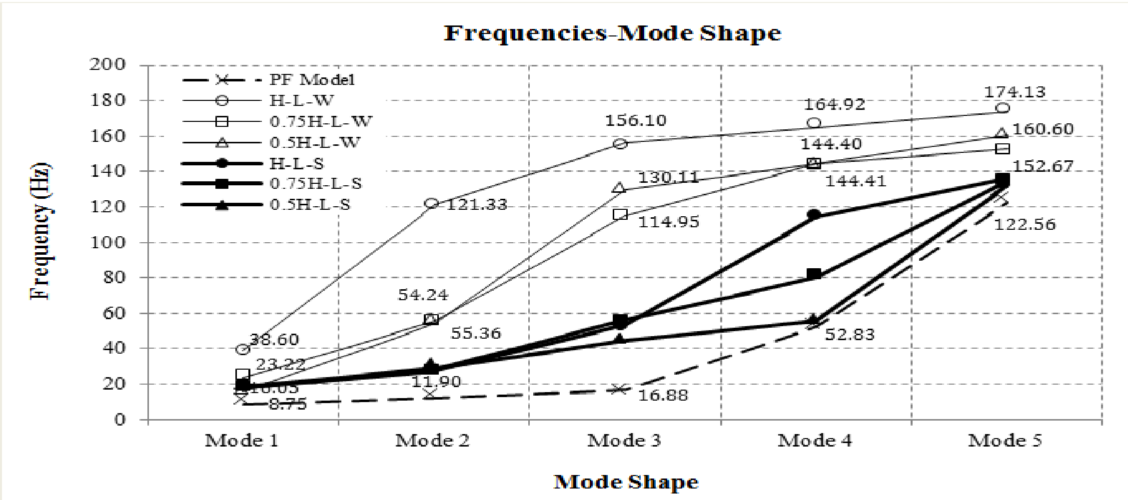


Figure 8. Comparison Natural Frequencies Between RC Frames with Infill Masonry Wall and Diagonal Compression Strut

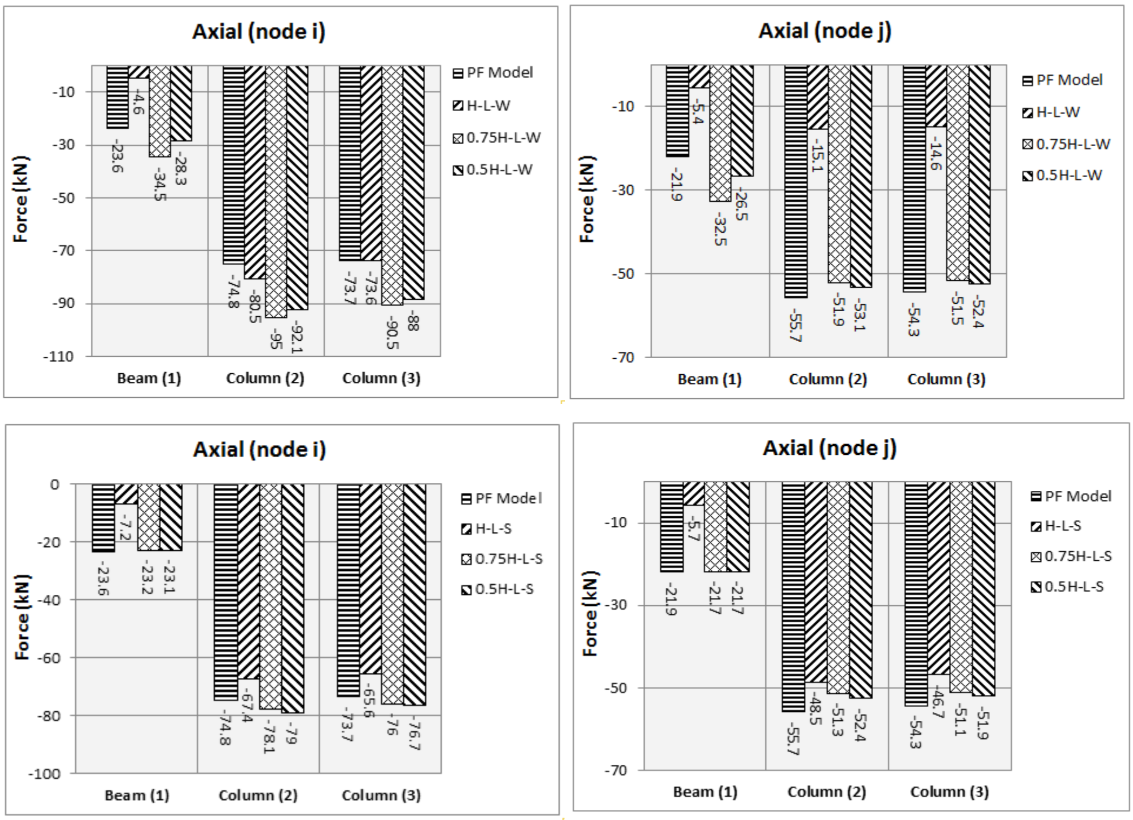


Figure 9. Comparison of Axial Force of Node i and j in Wall-Element and Strut Model

For axial force at both node i and node j of each element using the wall-element model and strut model are shown in Figure 9. In node i for the beam (1), no matter whether the wall element models or the strut models are used, the case with full wall has the smallest value and the stick model gives larger value than the wall element model by 36.00%. For wall element models, the axial force of 0.75 H-L-W is larger than that of 0.50 H-L-W by 18.00%, while the axial forces of 0.75 having the highest value. When the strut model is used, the full wall case has the smallest value and 0.50 H-L-W has the largest value. For the cases with partial wall, the difference in value for partial wall using the wall-element model and the strut model is very small. For the column (3), the trend is very similar to that of the left-side column. The only difference is that for the wall-element model the axial force of PF is almost the same as that of full wall case.

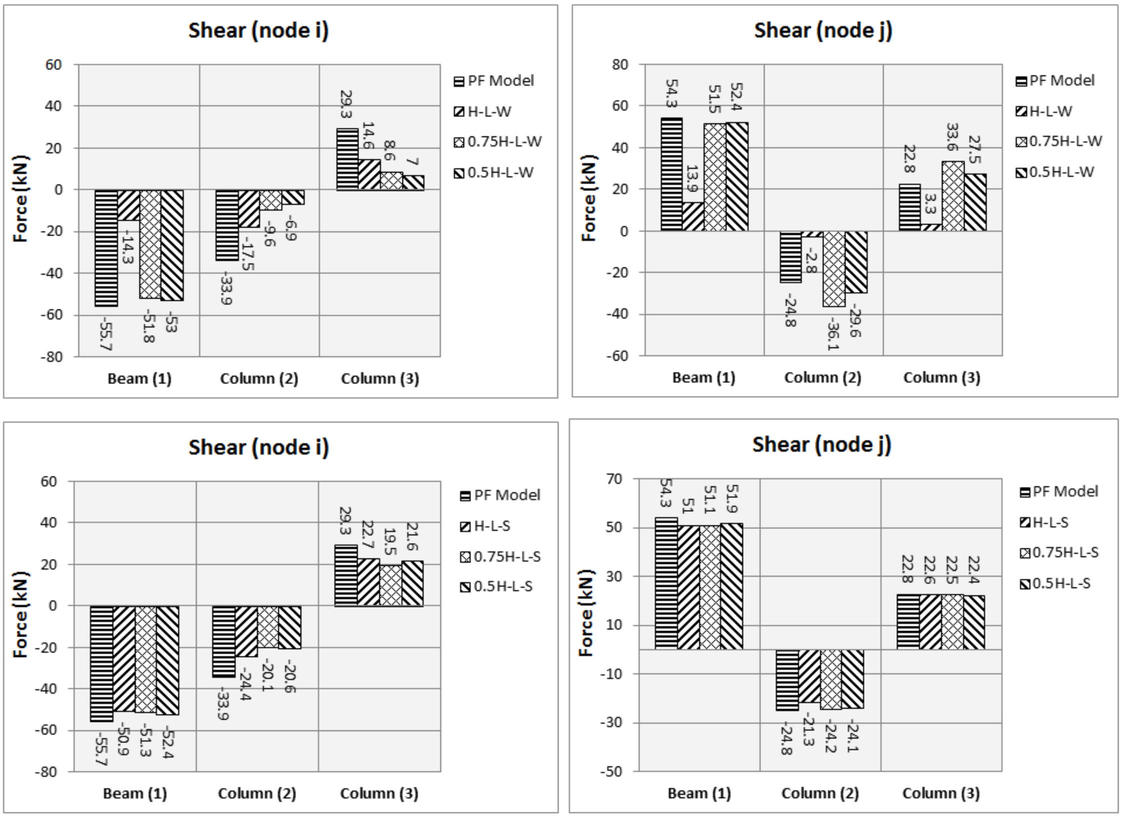


Figure 10. Comparison of Shear Force in Node i and j in Wall-Element and Strut Model

H-L-S and 0.50 H-L-S are almost the same. For the wall-element model the axial forces of partial wall are larger than that of PF, while for the strut model the axial forces of partial wall are slightly smaller that of PF.

For the column (2), when the wall-element model is adopted, the PF has the smallest axial force, while the axial forces of partial wall are larger than that of full wall by 19.00% with 0.75 H-L-W

In node j for the beam (1), the wall-element model and the strut model give almost the same axial force for full wall case. The axial force of the full wall is significantly smaller than that of PF and the partial wall case. for the partial wall case using the wall-element model, 0.75 H-L-W has larger value than 0.50 H-L-W by 19.00%, while for the partial wall case using the strut model, 0.75 H-L-W and 0.50 H-L-W have the same axial force.

For the Column (2) and the column (3), the trend is the similar for results obtained by the wall-element model and the strut model with PF having the largest value. The axial force of full wall case obtained by the wall-element model is about one-third of that obtained by the strut model. The difference in values of all models is not significant for strut model. For the wall-element model, the difference in values of PF and partial wall case are not significant, but the value of full wall case is far smaller than that of partial wall case and PF. The shear force of full wall case obtained by the wall-element model is about one-fourth of that obtained by the strut model.

For the column (2), in the wall-element model, the PF has the largest shear force, followed by H-L-W, 0.75 H-L-W and 0.50 H-L-W. For the strut model, the PF has the largest shear force, followed by H-L-W, 0.50 H-L-W and 0.75 H-L-W; however, the difference is not as significant as that of the wall-element model. For the cases with wall, the strut model gives larger value than the wall-element model. For the full wall case, the shear force obtained by the strut model is 1.40 times larger than that obtained by the wall model. The shear force of 0.75 H-L-S is 2.10 times larger than that of 0.75 H-L-W. The shear force of 0.50 H-L-S is 3 times larger than that of 0.50 H-L-W. For the column (3), the trend is similar to that of column (2). For the full wall case, the shear force obtained by the strut model is 1.60 times larger than that obtained by the wall model. The shear force of 0.75 H-L-S is 2.30 times larger

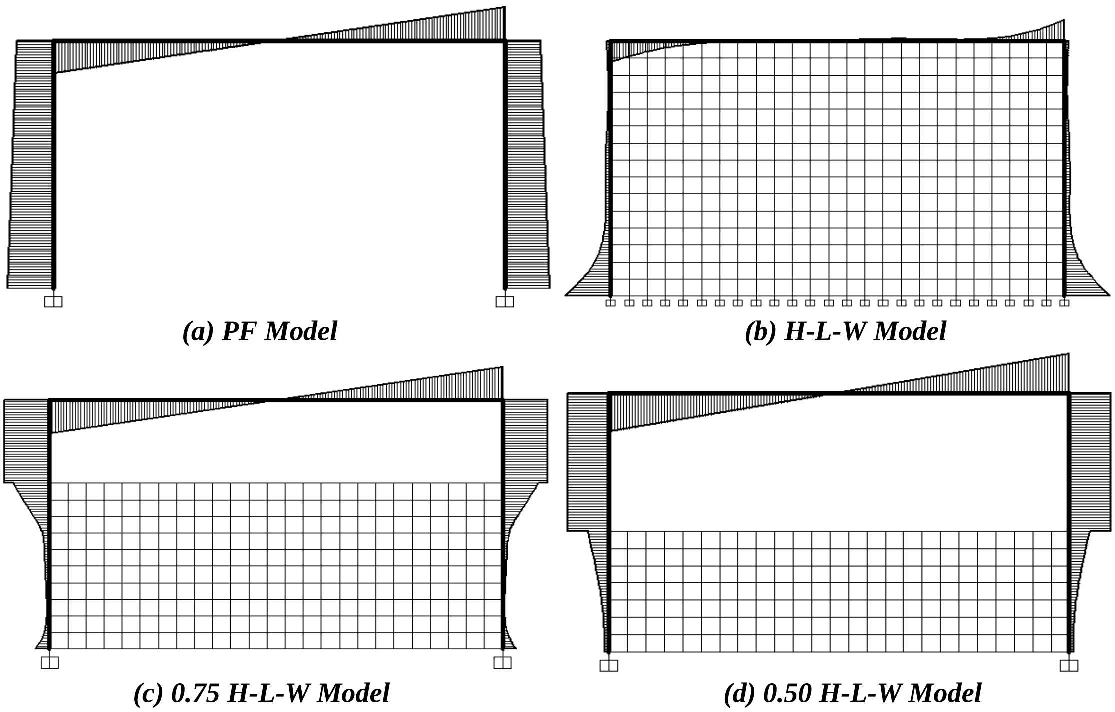


Figure 11. Distribution of Shear Force in Wall-Element Model with Infill Height Variation

As shown in Figure 10, for shear force in node i for the beam (1), the difference in shear force of all models is not significant for strut model. For the wall-element model, the difference in shear force of PF and partial wall case are not significant, but the shear force of full wall case is far smaller than that of partial wall case and PF. Except for the full wall case, the strut model gives almost the same values as the wall-element model. The shear force of full wall case obthan that of 0.75 H-L-W. The shear force of 0.50 H-L-S is 3.1 times larger than that of 0.50 H-L-W.

In node j for the beam (1), the difference in shear force of all models is not significant for using the strut model. For the wall-element model, the difference in shear force of PF and partial wall case are not significant, but the shear force of full wall case is far smaller than that of partial wall case and PF. Except for the full wall case, the strut model gives almost the same values as the wall-element model. The shear force of full wall case obtained by the wall-element model is about 30.00% of that obtained by the strut model.

For the column (2), the difference in shear force of all models is not significant for using the strut model. The shear force of full case using the wall-element model is very small as compared with that of partial wall case and PF. The shear force of full wall case using the strut model is 7.60 times larger than that using the wall-element model. The shear forces of the partial wall cases using the wall-element model are larger than that of PF. This indicates that there is short column effect for the part of column without wall. However, this phenomenon can not be predicted by using the strut model. 0.75 H-L-W has the shear force of 1.50 times larger than PF. 0.50 H-L-W has the shear force of 1.20 times larger than PF. This indicates that as the height of infill wall becomes smaller, the effect of short column will become smaller. For the column (3), the observations are similar to those of the column (2). The only difference is that the shear force of full wall case using the strut model is 6.90 times larger than that using the wall-element model. From the distribution of shear force along frame element in Figure 11 and Figure 12, the variation of shear force along the beam element is similar for all the models using the wall-element model and the strut model. The wall-element model can predict better the short column effect for the partial wall cases than the strut model as supported

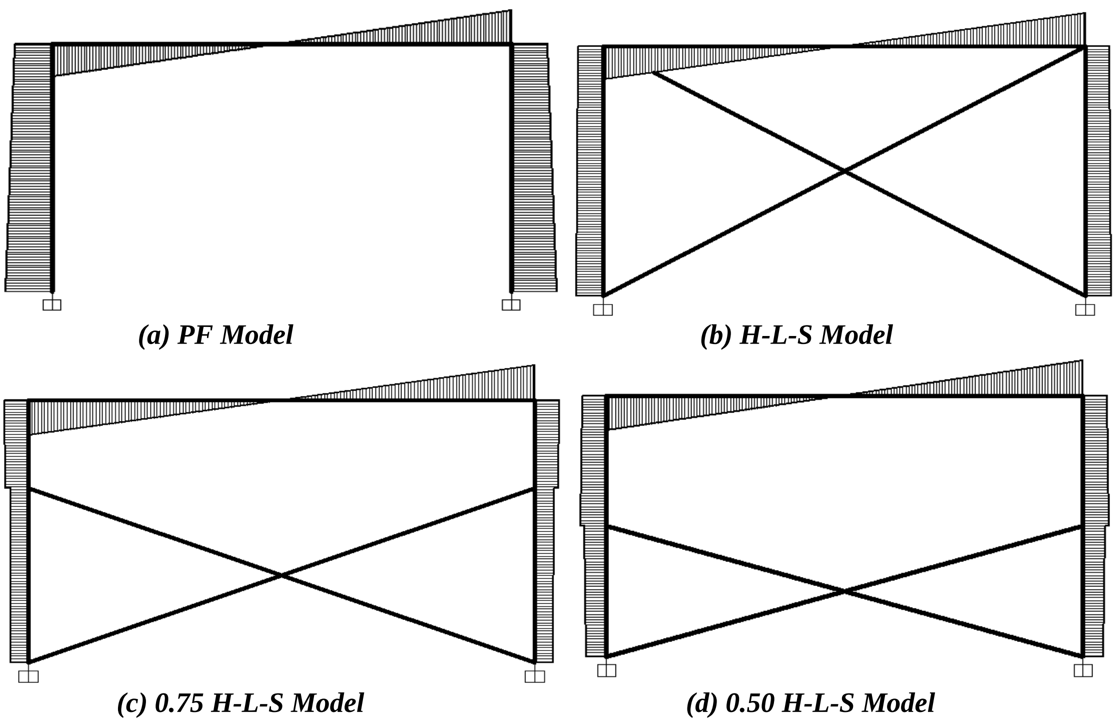


Figure 12. Distribution of Shear Force in Strut Model with Infill Height Variation

by Pradhan theory (2012) For the full wall case, the wall-element model gives very small value of shear force for the upper part of the columns, while the strut model does not render this phenomenon.

For the bending moment shown in Figure 13, in node i for the beam (1), the PF model has the largest bending moment. For the full wall case, the bending moment obtained using the wall-element model is 13.00% of that obtained using the strut model. Although small differences can be seen, the bending moments of partial wall cases do not change significantly. This may be due the fact that the wall does not have contact with the beam. The bending moment will become larger as the wall height decreases. The wall-element model gives the larger bending moment than the strut model by 10.00% for the partial wall cases.

For the column (2), the PF has the largest bending moment. For the strut model, the bending moment for the cases with wall decreases with decreasing wall height. However, for the wall-element model, 0.50 H-L-W has the highest value, followed by H-L-W and 0.75 H-L-W. The strut model gives the larger value than the wall-element model. For H-L-W, the strut model gives 1.80 times larger than the wall-element model. For 0.75 H-L-W, it is 1.70 times and for 0.50 H-L-W, it is 1.10 times. It seems that the difference decrease with decreasing wall height. For the column (3), the trend is similar to that of the column (2). The strut model gives the larger value than the wall-element model. For H-L-W, the strut model gives 2.10 times larger than the wall-element model. For 0.75 H-L-W, it is 1.80 times and for 0.50 H-L-W, it is 1.30 times. It seems that the difference decrease with decreasing wall height.

In node j for the beam (1), the PF model has the largest bending moment.

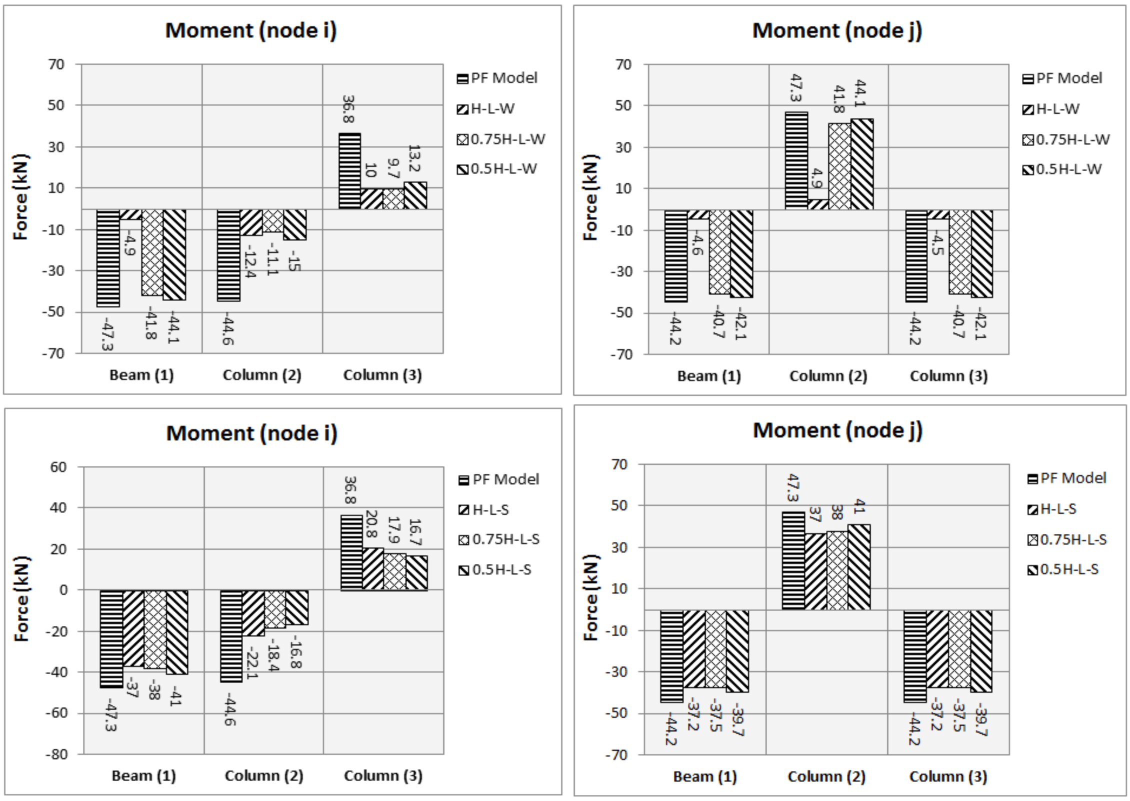


Figure 13. Comparison of Bending Moment in Node i and j in Wall-element and Strut Model

For the full wall case, the bending moment obtained using the wall-element model is 13.00% of that obtained using the strut model. Although small differences can be seen, the bending moments of partial wall cases do not change significantly. This may be due to the fact that the wall does not have contact with the beam. The bending moment will become larger as the wall height decreases. The wall-element model gives the larger bending moment than the strut model by 10.00% for the partial wall cases.

For the column (2), PF has the largest bending moment. For the strut model and wall-element model, the bending moment for the cases with wall increases with decreasing wall height. It is different as the i-end, the wall-element model gives higher value than the strut model for the partial wall cases. The wall-element model gives the larger value than the strut model for the partial wall cases. For 0.75 H-L-W, it is 1.10 times and for 0.50 H-L-W, it is 1.07 times. It seems that the difference decrease with decreasing wall height.

However, for full wall case, a very small value is obtained using the wall-element model, about 13.00% of that obtained by strut model. For the column (3) PF has the largest bending moment. For the strut model and wall-element model, the bending moment for the cases with wall increases with decreasing wall height. Unlike the i-end, the wall-element model gives higher value than the strut model for the partial wall cases. The wall-element model gives the larger value than the strut model for the partial wall cases. For 0.75 H-L-W, it is 1.08 times and for 0.50 H-L-W, it is 1.06 times. It seems that the difference decrease with decreasing wall height. However, for full wall case, a very small value is obtained using the wall-element model, about 12.00% of that obtained by strut model.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions drawn from this study are drawn as follow: (1) the infill masonry wall increases the stiffness of RC frame structure, as compared with pure frame model. Meanwhile, the diagonal strut model will give smaller natural frequencies than wall-element model; (2) when the part of the wall opening causes the wall to have no contact with a column, short column effect will be introduced in the column; (3) wall-element model can predict better the short column effect than the strut model; (4) although under static lateral load replacing masonry infill wall by diagonal strut was considered to be suitable for computing the response structure behaviour for the case without any opening in infill wall, but it is not the case for the dynamic analysis; and (5) different arrangement of infill wall in RC frame is not always beneficial to strengthen structure. Several modification of infill wall can induce larger forces therefore it should be analyzed case by case.

The recommendations of this study are as follows: (1) in this study only linear analysis was considered. To see how masonry infill wall will influence the seismic responses behaviour when strong earthquake occurs, it is better to consider non-linear analysis; (2) comparisons made for other equivalent strut width equations are necessary to obtain suitable formula with some modification for the case infill masonry wall with openings; and (3) In reality reinforced concrete frame structures are multi-story and multi-span structures, therefore it is recommended to study such structures to fully understand the role of masonry infill wall.

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