Nonlinear earthquake response analysis of RC frames with masonry infills

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SUMMARY:
In this study a comparison between three models including diagonal strut model, three strut model, and horizontal spring model for nonlinear analysis of reinforced concrete frames with masonry infill walls is presented. In diagonal strut model a masonry panel is replaced by equivalent single diagonal compression strut between the corners. In three strut model a masonry panel is replaced by one diagonal and two non-diagonal struts with force-deformation characteristics based on the orthotropic behavior of the masonry infill. In horizontal spring model a masonry panel is replaced by a horizontal shear spring between two nearby stories. Nonlinear pushover analysis was performed on series of RC plane frames with different number of stories and different layout of infill walls by SAP2000 program. Seismic performances of the frames were compared and effect of using different models were investigated.

Keywords: infill walls, earthquake response, diagonal strut, three strut, horizontal spring mode.

1. INSTRUCTION

In buildings, masonry fillers are used in interior and exterior walls for Architecture targets. Usually engineers assume masonry fillers (masonry infills) are non-structural and ignore interaction of masonry infills with around frame. When frames with masonry infills (composite frames) are subjected to lateral load, the masonry infill interacts with the surrounding frame and the effect of this interaction in stiffness and strength, is not able to ignoring. Interaction of infilled frame and masonry infill can be useful or harmful for structural performance.

When infilled frame are subjected to in-plan lateral loads, the frame and the masonry infill operate similar to monolith system at the first.The masonry infill are pressed in the compressive corner and are stretched in the tensile corner. Masonry infill is separated from the frame in tensile corner at the primary forces and cracks are created named “boundary crack” that specify boundary between frame and masonry infill. Different failure modes of masonry infilled frames can be imagined including: corner Crushing mode, Sliding shear, Diagonal compression, Diagonal cracking, Frame failure, which in this study is focused on corner Crushing mode.

The seismic codes like FEMA273, emphasize that contemplating masonry part in estimating seismic performance of existing buildings. Researchers produce many of analytical models for simulating masonry infills that they are using for studies, analytic and designing. In this study three macro models, diagonal strut model (FEMA273), three strut model (EL-Dakhakhni et al.) and horizontal spring model are chose and some composite frames are modelled in SAP200 software. In this study seismic performance of reinforced concrete frames with masonry infill walls are estimated and comparison between the three models is made.

2. Structures presentation for study

In this article the infilled frames for study are chose from two case, height (number of Storys) and number of infilled spans. The frames are 3, 5 and 7 Story and they have three spans with a length of 5 meters and the story height is 3.2 meters. Each frame is contemplated with three different arrangement of masonry infill include: three infilled spans (A type); two infilled spans (B type) and one infilled span (C type). For masonry infille walls the unit pressed brick are chose with the dimension 200x100x55mm that they produce masonry walls with a thickness of 20 cm. Totally 12 different structures are studied which are presented in table 2.1 and for example the three story structures are shown in Figure 1.

Table 2.1.naming frames

Number of story	Bare frame	Three infilled span (A type)	Two infilled span (B type)	One infilled span (C type)
3	3s-BF	3s-infA	3s-infB	3s-infC
5	5s-BF	5s-infA	5s-infB	5s-infC
7	7s-BF	7s-infA	7s-infB	7s-infC

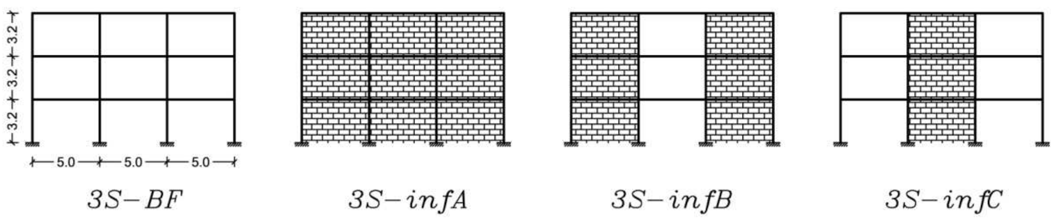

Figure 1. Three story structures

Beam and column cross-sections and longitudinal bars are presented in table 2.2. The specifications of the masonry infills (are used in Kabeyasawa and Mostafaei study) are obtained as:

-masonry strength perpendicular to bed joints; $f'_{m\text{-}90}$=44 kg/cm^2
-masonry strength parallel to bed joints; $f'_{m\text{-}0}$=30.8 kg/cm^2
-Young's modulus perpendicular to bed joints; E_{90}=33000 kg/cm^2
-shear modulus; G=13200 kg/cm^2
-masonry compression strain at the maximum compression stress; ε'_m=0.0018

Table 2.2. Beam and column cross-sections and longitudinal bars

The frames	story	Column section		Beam section		
		Dimension (cm)	Number of bars	Dimension (cm)	Number of bars at TOP	Number of bars at BOT
Three story	1st story	45x45	12Φ20	45x45	6Φ20	3Φ20
	2nd story	40x40	12Φ20	40x40	6Φ20	3Φ20
	3rd story	40x40	8Φ20	40x40	6Φ20	3Φ20
five story	1st story	50x50	20Φ20	50x50	8Φ20	5Φ20
	2nd story	50x50	14Φ20	50x50	8Φ20	5Φ20
	3rd story	50x50	12Φ20	50x50	8Φ20	5Φ20
	4th story	45x45	12Φ20	45x45	6Φ20	3Φ20
	5th story	40x40	8Φ20	40x40	5Φ20	3Φ20
seven story	1st story	60x60	20Φ20	60x60	9Φ20	7Φ20
	2nd story	60x60	16Φ20	60x60	9Φ20	7Φ20
	3rd story	60x60	16Φ20	60x60	9Φ20	7Φ20
	4th story	55x55	14Φ20	55x55	8Φ20	5Φ20
	5th story	55x55	12Φ20	55x55	8Φ20	5Φ20
	6th story	50x50	12Φ20	50x50	6Φ20	3Φ20
	7th story	45x45	12Φ20	45x45	4Φ20	3Φ20

3. Modelling of composite frame

The structures without masonry infill are designed on SAP2000 software. Moment plastic hinges, which are moment–rotation kind and PMM hing are used on start and end of the beam and columns.

3.1. Three struts model (EL-Dakhakhni et al.)

EL-Dakhakhni et al, replace masonry infills by one diagonal and two non-diagonal struts with force-deformation characteristics based on the orthotropic behavior of the masonry infill(Figure 2). They use Saneinejad and Hobbs (1995) equations for obtaining contact lengths and suggested a Simplified equation for calculating the total diagonal struts area as follows:

$$a_c h = \sqrt{\frac{2(M_{pj}+\beta_c M_{pc})}{t \cdot f'_{m-0}}} \leq 0.4h \tag{3.1}$$

$$a_b h = \sqrt{\frac{2(M_{pj}+\beta_{bc} M_{pb})}{t \cdot f'_{m-90}}} \leq 0.4L \tag{3.2}$$

$$A = \frac{(1-a_c)a_c ht}{\cos\theta} \tag{3.3}$$

Where α_c = ratio of the column contact length to the height of the column and α_b = ratio of the beam contact length to the span of the beam; *h*= column height and *l*= beam span. M_{pj}= minimum of the column's, the beam's or the connection's plastic moment capacity, referred to as the plastic moment capacity of the joint; M_{pc} and M_{pb}= column and the beam plastic moment capacities, respectively; σ_c and σ_c= normal contact stresses on the face of the column and beam, respectively; β_c and β_b= ratios between the maximum elastic field moment developed within the height of the column to M_{pc} and that developed within the span of the beam to M_{pb} ,respectively; and finally, *t*=thickness of the panel.

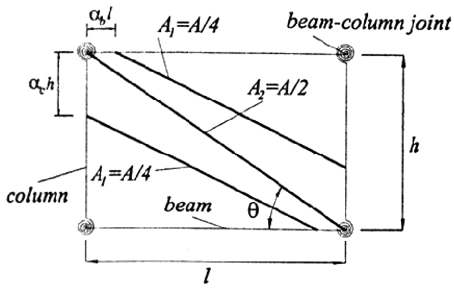

Figure 2. Three struts model (EL-Dakhakhni et al)

For developing orthotropic behavior of the masonry infill, constitutive relations of orthotropic plate (Shams and Cozzarelli 1992) and axes transformation matrix, are used to obtain the Young's modulus, E_θ , of the panel in the diagonal direction using the following equation:

$$E_\theta = \frac{1}{\frac{1}{E_0}\cos^4\theta + \left[-\frac{2v_{0-90}}{E_0}+\frac{1}{G}\right]\cos^2\theta\,\sin^2\theta + \frac{1}{E_{90}}\sin^4\theta} \tag{3.4}$$

Where E_0 and E_{90}=Young's module in the directions parallel and normal to the bed joints, respectively; v_{0-90}= Poisson's ratio defined as the ratio of the strain in the direction normal to the bed joints due to the strain in the direction parallel to the bed joints; and *G*= shear modulus.

Finally, the force-deformation relation for struts as shown in Figure3 is suggested to approximate it into a trilinear relation which the parameters are assumed according to the following:

$$E_p = 0.5E_\theta \tag{3.5}$$

$$\varepsilon_1 = \varepsilon_p - 0.001 \tag{3.6}$$

$$\varepsilon_2 = \varepsilon_p + 0.001 \tag{3.7}$$
$$\varepsilon_u = 0.01 \tag{3.8}$$

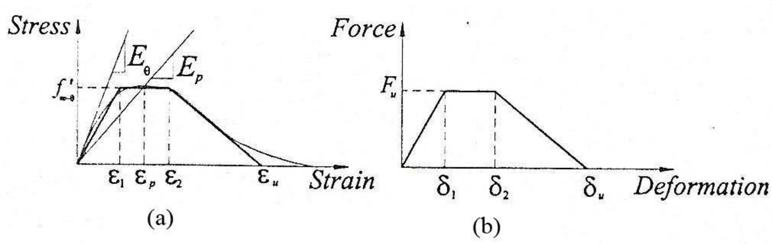

Figure 3. Simplified trilinear relations (EL-Dakhakhni et al):(a)Stress-strain relation for masonry, (b) typical force-deformation relation for struts

3.2. Diagonal strut model (FEMA273)

The FEMA273 suggests replacing of unreinforced masonry infill panel with an equivalent diagonal compression strut of width, *a* given by Equation as follows:

$$a = 0.175(\lambda_1 h_{col})^{-0.4} r_{inf} \tag{3.6}$$
$$\lambda_1 = \left[\frac{E_{me} t_{inf} \sin 2\theta}{4 E_{fe} I_{col} h_{inf}}\right]^{\frac{1}{4}} \tag{3.7}$$

Where h_{col}= Column height between center lines of beams (*in*), h_{inf}= Height of infill panel (*in*), E_{fe}= Expected modulus of elasticity of frame material (*psi*),E_{me}= Expected modulus of elasticity of infill material (*psi*), I_{col} = Moment of inertia of column (in^4),L_{inf}= Length of infill panel (*in*),r_{inf} = Diagonal length of infill panel (*in*), t_{inf}= Thickness of infill panel and equivalent strut (*in*), θ= Anglewhose tangent is the infill height-tolength aspect ratio (*radians*), λ_1= Coefficient used to determineequivalentwidth of infill strut.

For developing non-linear behavior of masonry infill on corner crashing mode, a force-deformation relation of Madan at al(1995), are chose (Figure 4). Values of the *a*, V_p and U_p are assumed according to the Kabeyasawa and Mostafaei study as follow:

$$V_p = 0.3V_m\,, \quad U_p = 3.5(0.01h_m - U_m), \quad \alpha = 0.2 \tag{3.8}$$

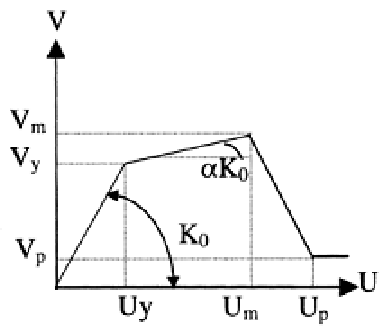

Figure 4. Strength envelope for masonry infill panel (Madan at al)

3.3. Horizontal spring model

Kabeyasawa and Mostafaei used a horizontal spring model equivalent of the diagonal compression strut in a Case study of Bam telephone center (Figure 5). They used the force-deformation relation of

Madan at al(1995) for developing the non-linear behavior of masonry infill on corner crashing mode.

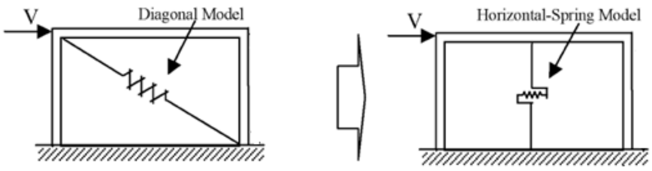

Figure 5.horizontal spring model equivalent of the diagonal compression strut

4. Estimating of composite frames and comparing between models

For estimating seismic performance of composite frames, nonlinear static analysis (Pushover analysis) is done and seismic performance levels in target displacement are determined. Load-Displacement relations of frames are shown in figures 6 to 10.

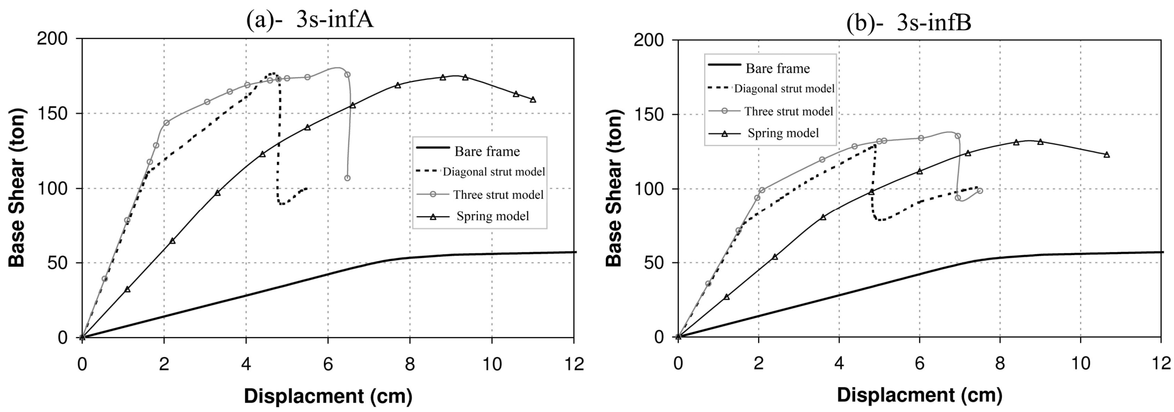

Figure 6. Load-Displacement relations:(a) 3s-infA; (b) 3s-infB

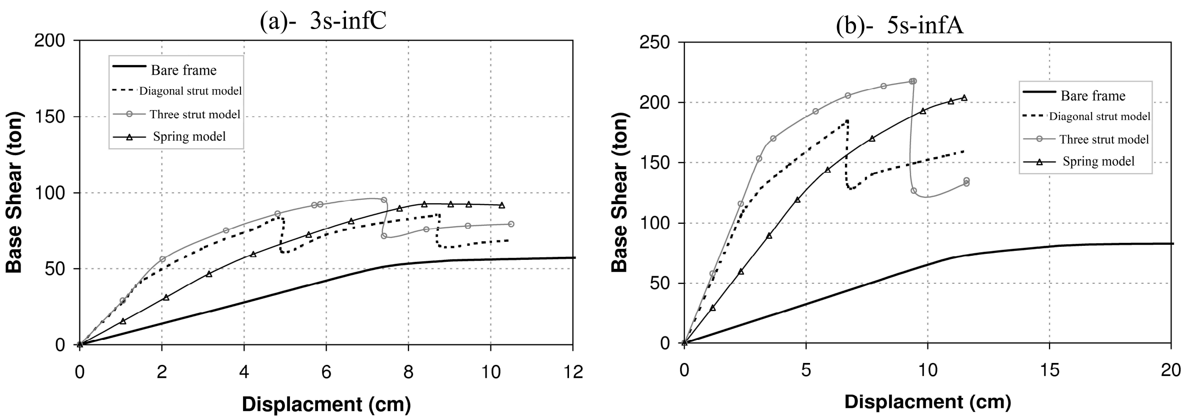

Figure 7. Load-Displacement relations: (a) 3s-infC; (b) 5s-infA

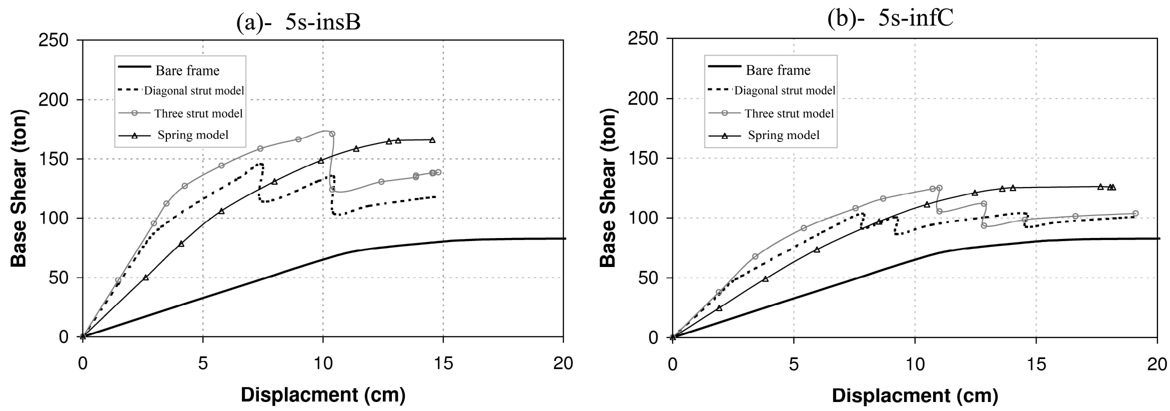

Figure 8. Load-Displacement relations: (a) 5s-infB; (b) 5s-infC

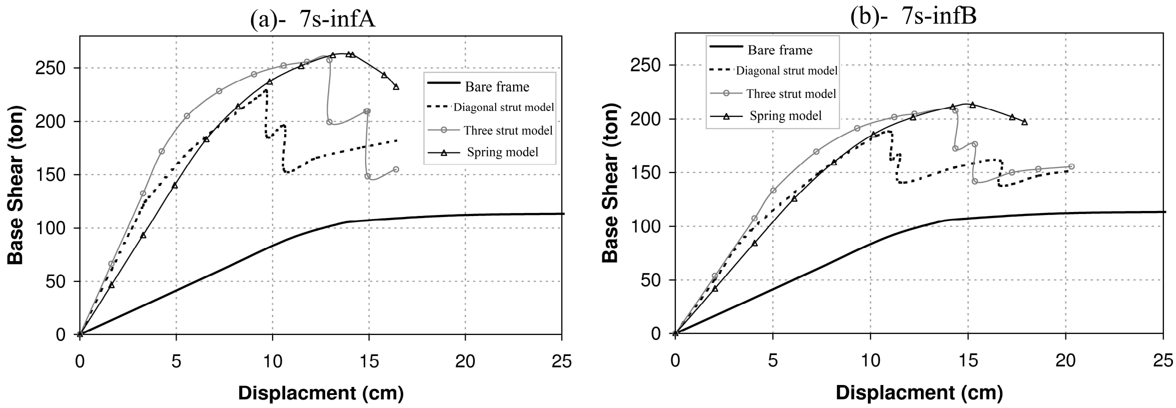

Figure 9. Load-Displacement relations: (a) 7s-infA; (b)7s-infB

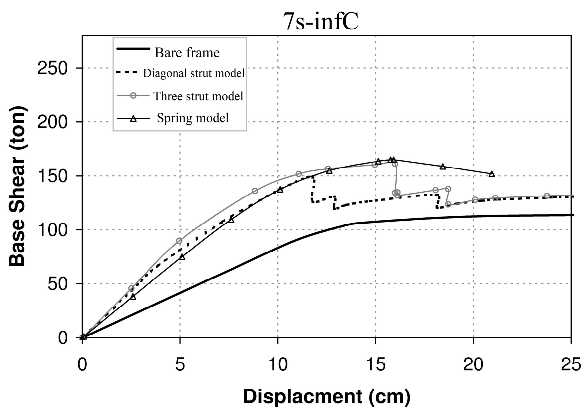

Figure 10. Load-Displacement relations of 7s-infC

The masonry infille caused increasing of frame strength which is very considerable. This increasing of effective stiffness is shown in figure 11. The diagrams show, with decreasing number of infilled span and with increasingnumber of story, the increasing of stiffness is declining. Approximately determining maximum of frame strength is equal with each model.

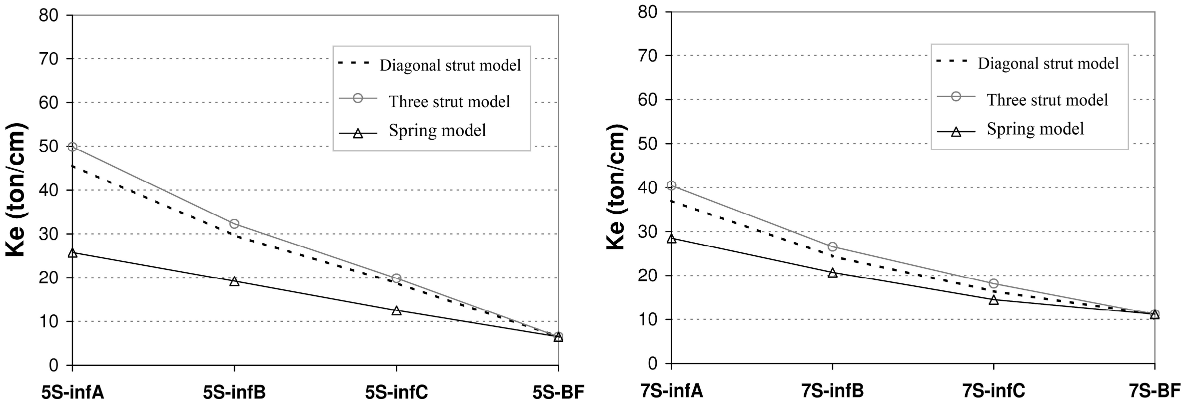

Figure 11. Effective stiffnessof 5 and 7 story frames

Masonry infille caused changing of distribution of plastic hinge and in some case changing of seismic performance levels. Also different macro model can develop different distribution of plastic hinge. For example in 3s-infA frame, seismic performance level is IO which with comparing with bare frame, masonry infille has positive effect and caused performance level reaching from LS (bare frame) to IO. With comparing the plastic hinge distribution of bare frame at the target displacement of infilled frame, the negative effect of masonry infille on around frame is observed.

Masonry infille caused decreasing of structure drift. Although masonry infille decrease the drift, but with collapsing masonry, specially at lower stories, caused increasing of drift suddenly and creating the soft story. The spring model determines the drift less than the other macro model in the lower stories and more than the other in the upper stories. Approximately determining of drift with Strut model and three struts model are the same. The drift of the 5s-infA and 7s-infA frame are shown in Figure 12.

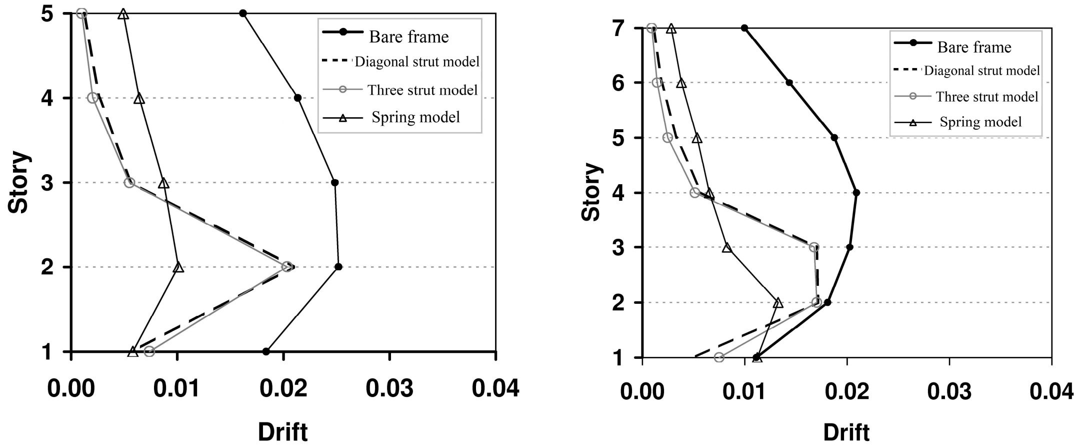

Figure 12. Drift of 5s-infA and 7s-infA

Masonry infille caused changing the distribution and amount of force in around frame. Moment of the beam and column decreased, but with collapsing the masonry in the middle stories, moment of the column increased suddenly. Increasing of shear in beam and column are observed. According the behavior of the composite frames and collapse mechanism, increasing of shear at the corner of the frames is expected in the contact length, which the simulation of three struts model in this subject is correct. In the spring model, distribution of the shear on the beam is different with the other macro model. Masonry infille caused increasing of axial force on column, which in three strut model obtained more than the other macro model.

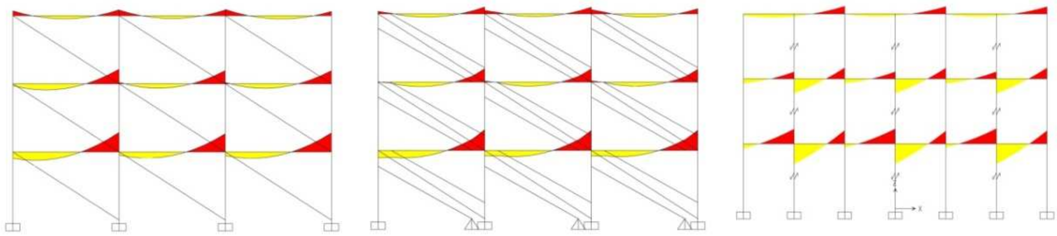

Figure 13. Bending moment diagrams on beam for 3s-infA

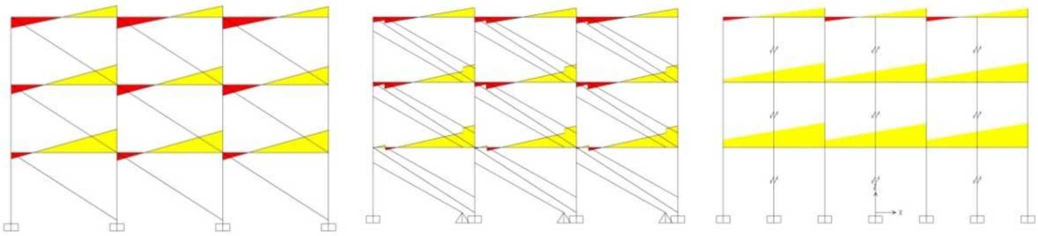

Figure 14. Shear diagrams on beam for 3s-infA

5. Conclusions

In this study the Seismic performances of masonry infiled frame and the comparing between three macro model for the simulating non-linear bevavior of composite frame, have been discussed. The results of Pushover analyses (focusing on the 2D analyses) on frames have been presented and confirming of masonry infille caused increasing of frame strength and frame stiffness.

Increasing of strength and stiffness is declining, by decreasing number of infilled span and increasing number of story. The three strut model obtains the initial stiffness less than the diagonal strut model (between 3% to 9%), and this different is declining by decreasing number of infilled span and number of story. The spring model obtains the initial stiffness less than the other macro model about 57 percent. This different on spring model is declining by increasing number of story.

Masonry infille caused changing the distribution of plastic hinge and in the some case changing the seismic performance levels. The method of modelling influences distribution of plastic hinge. Distribution of plastic hinge in spring model is different to other macro model. The seismic performance levels of masonry in spring model are not specific because type of modelling. Also the spring model does not show soft story happening in lower stories.

Decreasing of structure drifts are developed because of existing masonry infille and also soft story is developed because of collapsing the masonry specially at lower stories. The spring model determines the drift less than the other macro model in the lower stories and more than in the upper stories. Both of the Strut model and three struts model determine the drift approximately the same.

Distribution and amount of force in around frame are changed because of existing masonry infille. Moment of the beams and columnsare decreased, but with collapsing the masonry in the middle stories, moment of the column increased suddenly. Increasing of shear in beams and columns are observed. According the behavior of the composite frames and collapse mechanism, increasing of shear at the corner of the frames is expected in the contact length, which the simulation of three struts model in this subject is correct. In the spring model, distribution of the shear on the beam is different with the other macro model. Masonry infille caused increasing of axial force on column, which in three strut model obtained more than the other macro model.

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