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Effects of Infill Panels with Various Configurations on the Non-Linear Dynamic Responses of Reinforced Concrete Structures

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Abstract: This study presents the effects of including infill panels on the non-linear dynamic response of a hypothetical reinforced concrete frame when subjected to an earthquake. Infill panels are represented by equivalent diagonal struts using three different configurations, i.e., single, double with three different connection locations with the beams, and triple struts. The main goal is to determine the simplest and most appropriate representation of the infill panels by analogous struts. The effect of panel sizes on the non-linear dynamic response of the structure is also presented in this work. The main results showed that including infill panels in the analysis reduced the natural period, roof displacement, and story drift ratio, increasing the roof acceleration and shear forces at the structure base. Utilizing the triple model and the double strut joined at the midspan of the beams showed a good agreement with those using the complete infill model.

تأثير جدران الاملاء وبتكوينات مختلفة على الاستجابة الديناميكية غير الخطية للهياكل الخرسانية المسلحة

ميسم نبيل محمد، حلا جاسم محمد، محمد نجم محمود
قسم الهندسة المدنية / كلية الهندسة / جامعة الموصل / الموصل - العراق.

الخلاصة
تعرض هذه الدراسة تاثير تضمين ألواح االاملاء على الاستجابة الديناميكية اللاخطية لهياكل خرسانية مسلحة افتراضية عند تعرضه لزلزال. تم تمثيل ألواح االاملاء بدعامات قطرية مكافئة باستخدام ثلاثة تكوينات مختلفة (مفردة ومزدوجة مع ثلاثة مواقع اتصال مختلفة مع العنب والدعامات الثلاثية). الهدف الرئيسي هو تحديد التمثيل الأبسط والأنسب لألواح الاملاء بواسطة دعامات مكافئة. تم أيضًا في هذه الدراسة عرض تأثير أحجام الواح الاملاء على الاستجابة الديناميكية غير الخطية للهيكل. أظهرت النتائج الرئيسية أن تضمين ألواح الاملاء في التحليل يؤدي إلى انخفاض في الفترة الطبيعية، وإزاحة السقف ونسبة انحراف الطوابق مع زيادة في تسارع السقف وقوى القص عند قاعدة الهيكل. أظهر استخدام النموذج الثلاثي والدعامة المزدوجة المرتبطة في منتصف العتب اتفاقًا جيدًا مع تلك التي تم استخدام نموذج الواح الاملاء الكاملة.

الكلمات الدالة: ديناميكي، هزة ارضية، الواح الاملاء، التحليل غير الخطي، مفصال بلاستيكية.

1.INTRODUCTION

Due to their architectural requirements or aesthetic appeal, infill panels are frequently employed in structures building as partitions. Due to the lack of an accurate and simple analytical model, the infill panels are often ignored in the non-linear analysis of reinforced concrete structures. This ignorance could lead to an incorrect prediction of the dynamic response of these structures when subjected to earthquake loads. Neglecting the infill panels during analysis and design could lead to an overestimation of the design of these buildings, particularly when lateral loading is considered, as these panels provide concrete structures with a significant degree of lateral strength and stiffness. Contractors typically construct infill panels, also known as partitions, after completing the reinforced concrete frame. Researchers simply regard these panels as a static load on the frame in the analysis. Researchers have thoroughly studied the impact of these panels on the dynamic response of reinforced concrete structures, and the following paragraphs provide a summary of the latest related research. Fotos et al. [1] conducted a study utilizing the pushover analysis technique. The objective was to comprehend the effects of completely or partially filling walls in four distinct buildings. Contrast this situation with a structure that lacks any partitions. The buildings varied in height, ranging from four to ten stories. Upon analysis, it was observed that structures with partition walls exhibited greater robustness compared to those without such panels. Zahir and Garg [2] explored how wall partitions influence the dynamic behavior of a 10-story concrete building. Their analyses showed differences in support reactions, natural period, drift ratios, roof movement, and story shear when compared to a bare framework. Ömer [3] analyzed a single-panel, one-story reinforced concrete frame. In the analytical model, diagonal bracing replaced the brick partition. The bracing included single, double, and triple struts. The predicted results were compared with the experimental data. The experiments showed better initial stiffness and strength in structures infilled with brick wall partitions. These also lessen side sway and story drift ratios. The model with three struts showed the best response. Sankhla and Bhati's [4] focused on a 20-story concrete building incorporating various partition panel designs within the framework. They assumed that the panels were in the form of single or double diagonal braces. Factoring the panels into the analysis significantly minimized the side sways, compared to just considering the basic frame. Mehani et al. [5] used pushover analysis and macro modeling to look at how infill panels affect the sideways movement of a five-story reinforced concrete building. According to the results, a structure with brick partitions shows approximately 23 percent reduced displacement compared to a frame without any panels. Moreover, the natural period of the structure with the inclusion of these panels was about 25 percent lower compared to the bare frame. Mahmud et al. [6] employed numerical techniques to examine the impact of including infill panels on the seismic response of a single-story reinforced concrete frame. The inclusion of these panels was found to increase the base shear of the structure, and that was attributed to the increase in its lateral stiffness. Ucar [7] modeled brick wall partitions as equivalent diagonal braces to assess their influence on a reinforced concrete structure subjected to earthquakes. The results showed that adding these partitions increased the base shear, made the structures stronger in shear compared to frames without partitions, and greatly reduced the lateral displacements. Halla [8] conducted an investigation to evaluate the behavior of infill panels and determine the ideal width of the strut to represent them. Each structure was examined four times: first, with infill panels, and second with an equivalent diagonal strut whose width was determined using FEMA code [9], Holmes [10], Paulay, and Priestley [11] modeling. The results showed that the effective width of the equivalent diagonal strut before cracking was within (0.3 dm), while the effective width in the post-cracking stages was (0.1-0.25 dm), where dm is the diagonal length of the infill panel. Halla and Mohamad [12] investigated the impact of infill panels on the dynamic response of reinforced concrete structures with an isolated and fixed basis of 11-story reinforced concrete structures. The results showed that the infill panels reduced the roof acceleration, displacement, and story drift ratios by 77.5%, 78.6%, and 82.9%, respectively, increased the percentage of elastic energy, and decreased the percentage ratio of inelastic energy in the isolated building. Zine et al. [13] applied pushover analysis to three structures with 2, 4, and 8 stories. Each structure was examined as a bare frame with two different infill panel distributions, completely or partially. The results showed that the infill panels improved the seismic response, initial stiffness, and strength of reinforced concrete buildings. The responses to the two- and four-story structures differed from those for the eight-story structure. From the above critical review, there is a gap regarding studying the effects of spans of infill panels on the response of reinforced concrete buildings when these panels are modeled as corresponding struts using different configurations.

2. METHODOLOGY

In the present work, a non-linear dynamic analysis was carried out for hypothetical reinforced concrete (RC) structures under the effect of the EL Centro earthquake record that is available in the SAP2000 software [14]. The analysis was conducted to evaluate the effects of modeling the infill panels by 1, 2, and 3 equivalent diagonal struts and the effects of the location of the multiple diagonal struts and their connections with the beams and columns on the non-linear dynamic response of the considered structures exposed to an earthquake. Comparisons were made with similar structures with a full-infill panels model or a bare frame. The relative energy equation can be stated by integrating the time domain multi-degree of freedom equation of motion on relative displacement, as follows [15]:

$$\int_0^t M\ddot{u}(\tau)du(\tau) + \int_0^t C\dot{u}(t)\,du(\tau) + \int_0^t Ku(\tau)du(\tau) = -\int_0^t MI\,\ddot{u}_g(\tau)du(\tau) \quad (1)$$

Where M is the mass matrix, C is the damping matrix, K is the stiffness matrix, u(τ) is the relative displacement at time τ, I is the identity matrix, and $\ddot{u}_g(\tau)$ is the ground acceleration at time τ. In the present work, the Classical Rayleigh damping was implemented to compute the damping matrix C as [8,9]:

$$\mathbf{C = \mu M + \lambda K} \quad (2)$$

Where μ and λ are the mass and stiffness proportional Rayleigh damping coefficients, respectively. Each of these proportional coefficients, i.e., μ and λ, depends on the structure's response frequencies or natural period. The damping ratios ξi and ξj for the i^{th} and j^{th} modes were assumed to be constant and equal to ξ=0.05 and used to compute the coefficients μ and λ. Thus, these coefficients are computed by [14]:

$$\begin{cases} \mu = \xi \dfrac{2\omega_i\omega_j}{\omega_i + \omega_j} \\ \lambda = \xi \dfrac{2}{\omega_i + \omega_j} \end{cases} \quad (3)$$

Where ωi and ωj are the response frequencies in rad/s for the ith and jth modes. The non-linear hinge properties were assigned (P-M2-M3) fiber hinges at the two ends of the columns and beams [14]. In this modeling, the cross section's concrete was subdivided into a predetermined number of regions. The stress in each region was calculated based on that member's loading condition, i.e., axial force and biaxial moments. Additionally, the primary bars, positioned precisely where they should be in the cross-section, were examined for stress status concurrently. The state of the plastic hinges was checked at both ends of each member; these were based on the compressive strength of concrete (fc'=28MPa), the tensile strength of concrete (ft=3.28MPa), and the elastic modulus (Ec=25028MPa) with a steel yield stress of (400MPa). The slabs were meshed using four nodes of shell elements with (1x1m) meshes. Accordingly, the peripheral beams were subdivided into a mesh with (1m) size. The struts were treated as no-tension members and given axial (P) hinge qualities when in compression. Before beginning the non-linear time history analysis for the consequences of an earthquake, a preliminary non-linear static analysis was carried out under the load combination of dead loads and 0.3 of live loads in the gravity direction.

3. DESCRIPTION OF THE BUILDINGS

A parametric study was carried out on three hypothetical RC structures, each with eight stories (Ground+7), with each story height equal to 3m. All structures with square plans varied in size (3x3, 5x5, and 6x6 m), meaning each structure only has one span in the X and Y axes. These structures are shown in Fig. 1, modeled by SAP2000 (V23) software [14]. The thickness of the infill panels was assumed to be equal to 200mm, with a compressive strength of 8MPa and an elastic modulus of 13378MPa [8]. The slab, which had a thickness of 150mm, was modeled as a rigid diaphragm subjected to a uniform dead load of 2.5kPa in addition to the self-weight of the structure and a live load of 3kPa. The beam's dimensions were (300x500 mm) reinforced with (3Ø16) top and bottom bars for the three buildings, while the column's size for buildings with (3×3m) spans was (300x300 mm) with (4Ø20) main reinforcement. For a building with (5×5m) spans, the column's size was (350x350 mm) with a main reinforcement of (4Ø25), and for a building with (6×6m) spans, it was (400x400 mm) with a main reinforcement of (8Ø20).

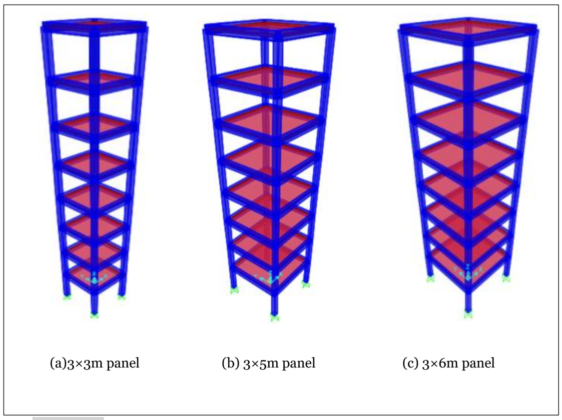

Fig.1 Three Models with Different Spans.

4. EQUIVALENT STRUT MODEL FOR THE INFILL PANELS

In the present work, infill panels are represented exclusively as an analogous diagonal strut in the X direction, which is the direction of the applied earthquake effect, using single, double, and triple struts. The struts' effective thickness (W) was assumed equal (200mm) based on the presumption that the infill panels were built from concrete blocks. The equivalent diagonal strut's width of (0.25dm) was used in the present study, where dm is the diagonal length of the infill panels, which was proved by Halla [8] and Ref. [12] to be the optimal width and provides the best agreement with Smith and Coull [16] and Paulay and Priestley's [11] experimental work. The infill panels were implemented in the X direction as an equivalent diagonal strut, with different configurations, i.e., single, double, and triple. Each structure was analyzed under five different conditions. These were bare frames, frames with full infill panels, frames with single struts, frames with double struts with different connection locations with the beams, i.e., 0.2L, 0.35L, and 0.5L where L is the span length, and frame with triple struts, as shown in Fig. 2. The width of each strut using two struts was equivalent to half of a quarter of the diagonal length of the infill panel (0.125dm). In the triple struts model, the central diagonal strut's width was equal (0.125dm), and the off-diagonal strut's width was equal to half of the central strut's width. Therefore, the overall width of all comparable struts was equal to one-fourth of the diagonal length of the infill panel. The width of the struts is given in Table 1. For various types of implemented struts, the positions of the connection of the strut with the beams and columns are given in Table 2.

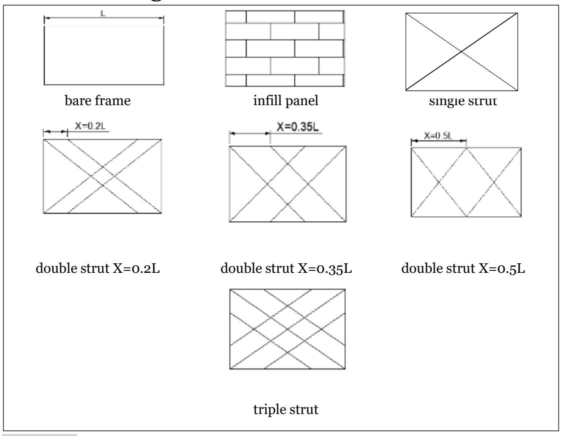

Fig.2 Shows the SAP2000 Models of Different Strut Configurations.

Table 1 The Width of the Struts.

Struts	Panel size (m)	width of each strut (mm)
Single strut	3×3	1060
	3×5	1500
	3×6	1680
Double strut	3×3	530
	3×5	750
	3×6	840
Triple strut	3×3	530
	3×5	750
	3×6	840

Table 2 Location of Strut Connections with Beams and Columns.

Struts	Spaces (m)	Location of strut connection	Connection on beams (mm)	Connection on columns (mm)
Single strut	3×3	-	-	-
	3×5	-	-	-
	3×6	-	-	-
Double strut	3×3	X=0.2L	600	-
		X=0.35L	1050	-
		X=0.5L	1500	-
	3×5	X=0.2L	1000	-
		X=0.35L	1750	-
		X=0.5L	2500	-
	3×6	X=0.2L	1200	-
		X=0.35L	2100	-
		X=0.5L	3000	-
Triple strut	3×3	-	750	750
	3×5	-	1460	875
	3×6	-	1876	938

5. RESULTS AND DISCUSSIONS

The obtained results from non-linear dynamic analysis are discussed here. The presented results illustrate the impact of the aspect ratio (L/h) of infill panels on the dynamic response of the structure when infill panels are included in the analysis of these structures using the different configurations stated above. The details of these three buildings having different panel sizes, 3×3m, 3×5m, and 3×6m, are presented in Fig. 1. Figs. 3-5 show that including the infill panels in the analysis reduced the structure's natural period. By increasing the panel span, the percentage of these reductions increased compared to the bare frame. The average reductions were 49%, 51%, and 72% for the 3×3m, 3×5m, and 3×6m panel sizes, respectively. By scrutinizing these figures, it can be concluded that double struts with x=0.5L gave the closest natural period values to those when full-infill panels were used. Similar reductions in response can be noticed for the variation of roof displacement with time, as shown in Figs. 6-8. According to these figures, each of the six modeling types of infill panels experienced the same response during the first two seconds of the earthquake. Any modeling type incorporating infill panels significantly decreased the roof's lateral displacements, especially for larger panel sizes (3x6m). The vibration frequency of the three structures and damping, especially for the structure with the largest (3x6m) panel size, increased due to including the infill panels. This increase in damping resulted from the fact that the damping matrix was calculated using Rayleigh proportional damping, which depends on the mass and stiffness matrices of the structure, as given in Eq. 2; this can be explained by the fact that the added infill panels to the structure increased its mass and rigidity, which in turn increased the damping. Also, significant reductions were obtained in the maximum positive and negative drift ratio when infill panels were included in the analysis, as shown in Figs. 9-11, where positive drift is associated with the positive lateral deflection of the structure and negative drift is associated with the negative lateral deflection. As can be noticed that the least positive and negative drift ratio was obtained when full infill panels were included in the analysis compared to that of bare frame; however, the other types of modeling the infill panels using struts with different configurations gave a close drift ratio to that of full infill. Figs. 12-14 depict the variation in roof acceleration over time for buildings with the 3×3m, 3×5m, and 3×6m panel sizes, respectively. These figures showed an increase in the maximum positive and negative acceleration when infill panels were included in the analysis of these buildings with different configurations of struts. These three figures demonstrate that all had close results in the first two seconds when the largest roof acceleration occurred, full infill modeling, double strut modeling with x=0.5L, and triple modeling. The average percentages of these increases were 105%,120%, and 97% for buildings with the 3×3m, 3×5m, and 3×6m panel sizes, respectively. The corresponding percentages of negative increases were 51%, 77%, and 79%, as indicated in the same figures. The variation of base shear for the seven models with different panel sizes is presented in Figs. 15-17 indicate an increase in the base shear values with the inclusion of infill panels, which is a potentially dangerous phenomenon since ignoring the infill panels in the dynamic analysis will result in an underestimation of the shear at the base of the building, which must be sustained by the columns on the ground floor. The average percentages of these increases were 136%, 160%, and 206% for the 3×3m, 3×5m, and 3×6m panel sizes, respectively. Finally, scrutinizing these figures, it was concluded that utilizing the double strut with X=0.5L and the triple strut produced the closest results to those of full infill so that the strut model may consider it the most appropriate representation of infill panels.

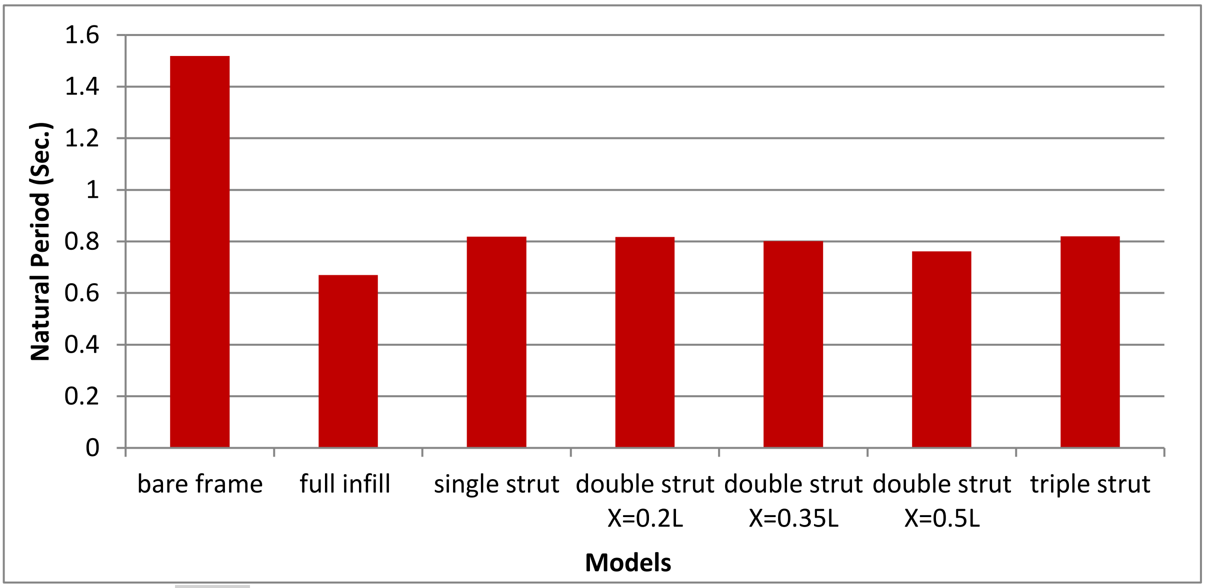

Fig.3 Natural Period for Different Models for Building with 3×3m Panel.

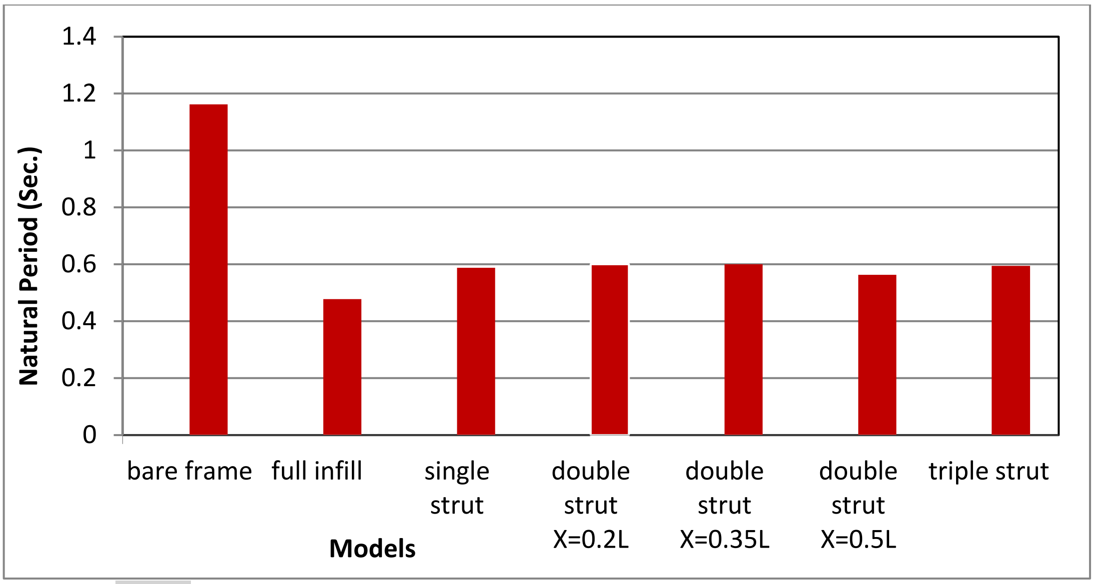

Fig.4 Natural Period for Different Models for Building with 3×5m Panel.

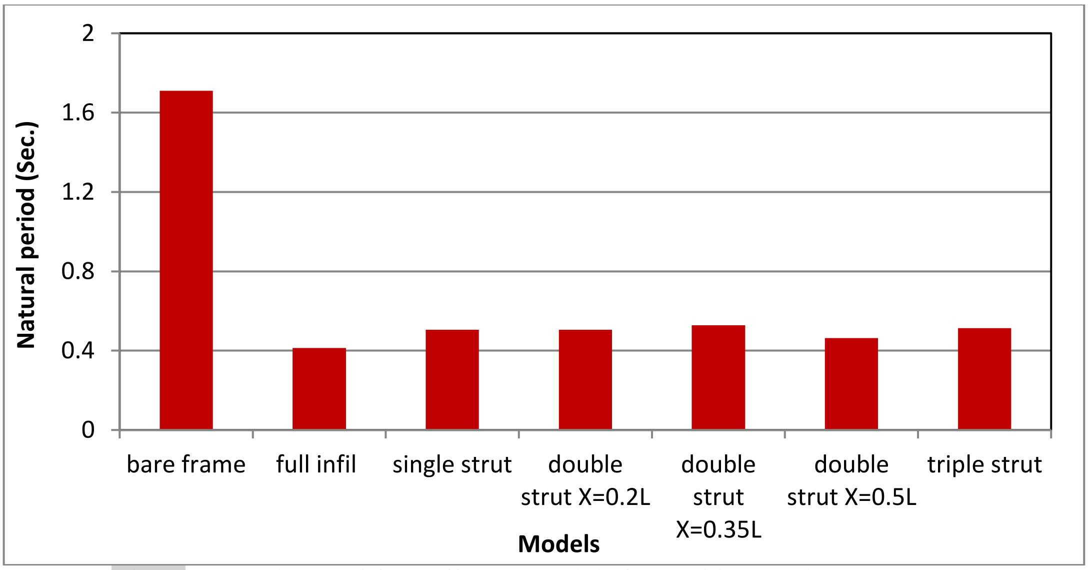

Fig.5 Natural Period for Different Models for Building with 3×6m Panel.

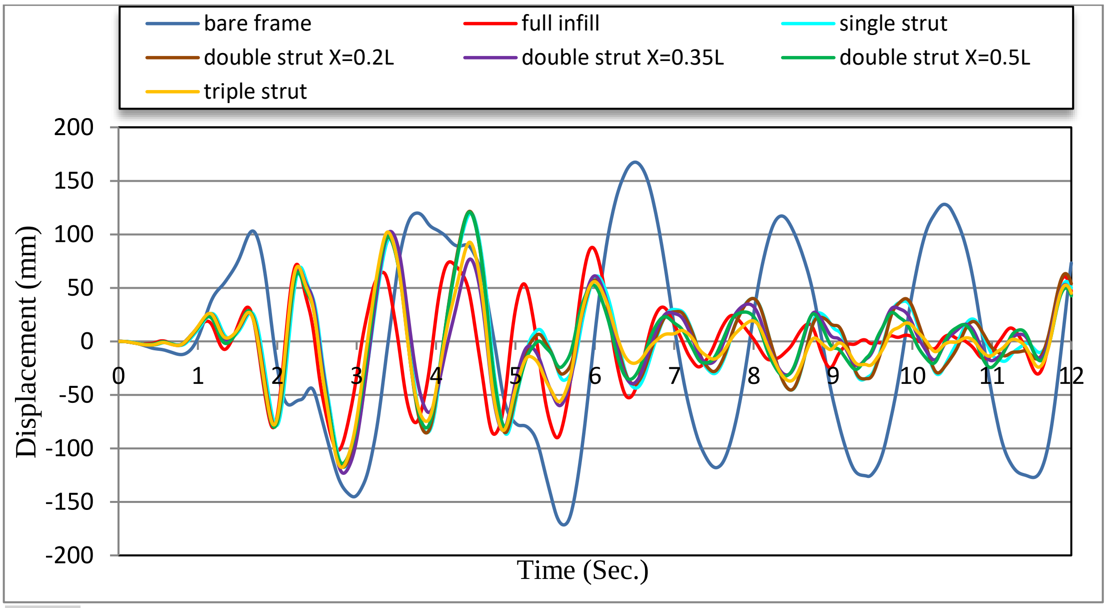

Fig.6 Effect of Including Infill Panels on Roof Displacements for Building with 3x3m Panels.

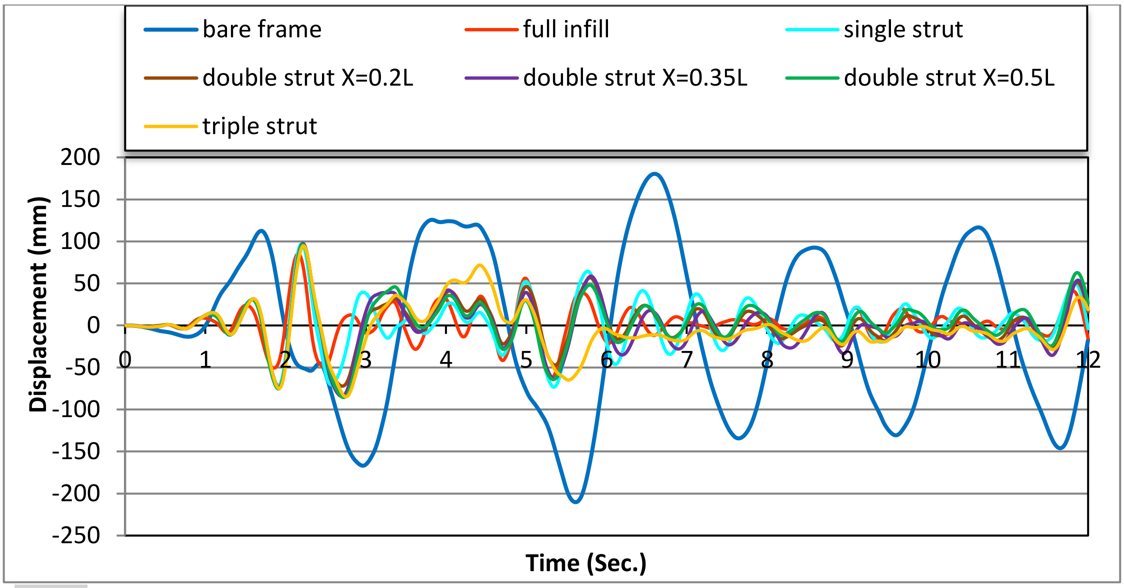

Fig.7 Effect of Including Infill Panels on Roof Displacements for Building with 3x5m Panels.

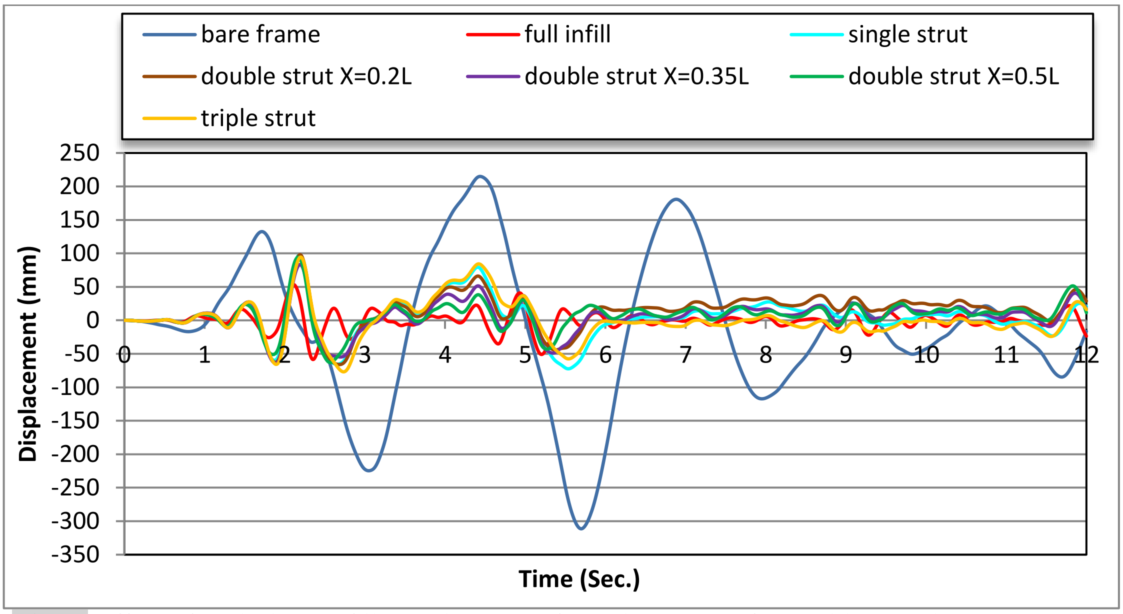

Fig.8 Effect of Including Infill Panels on Roof Displacements for Building with 3x6m Panels.

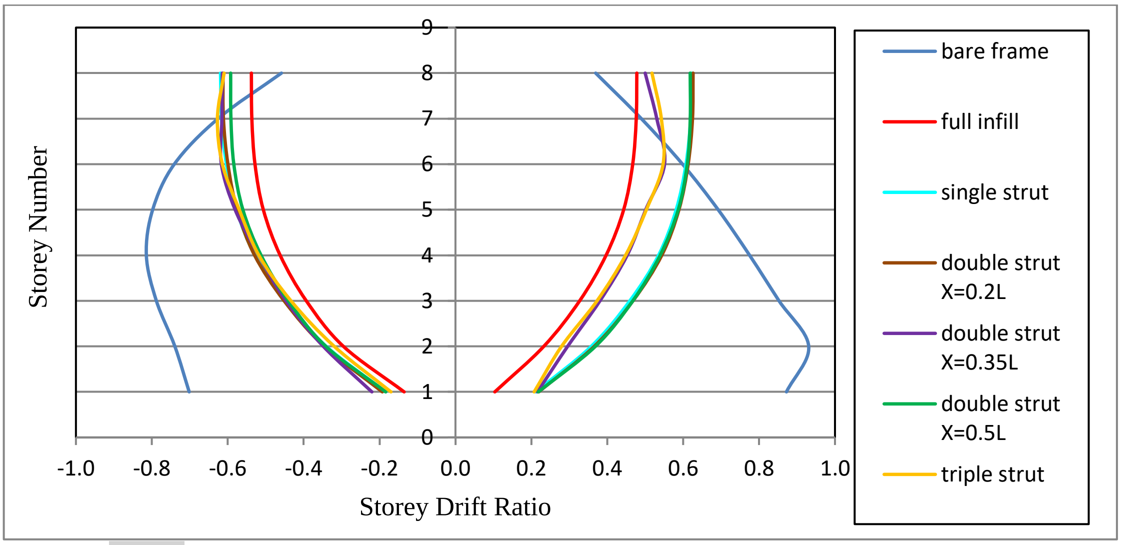

Fig.9 Story Drift Ratio for the Seven Models for Building with 3×3m Panels.

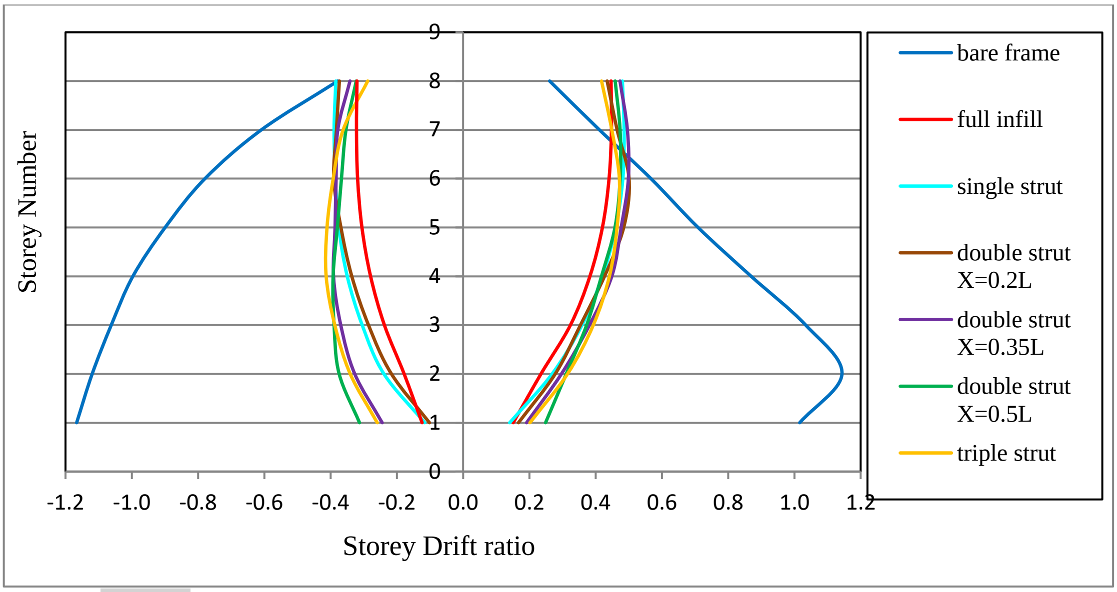

Fig.10 Story Drift Ratio for the Seven Models for Building with 3×5m Panels.

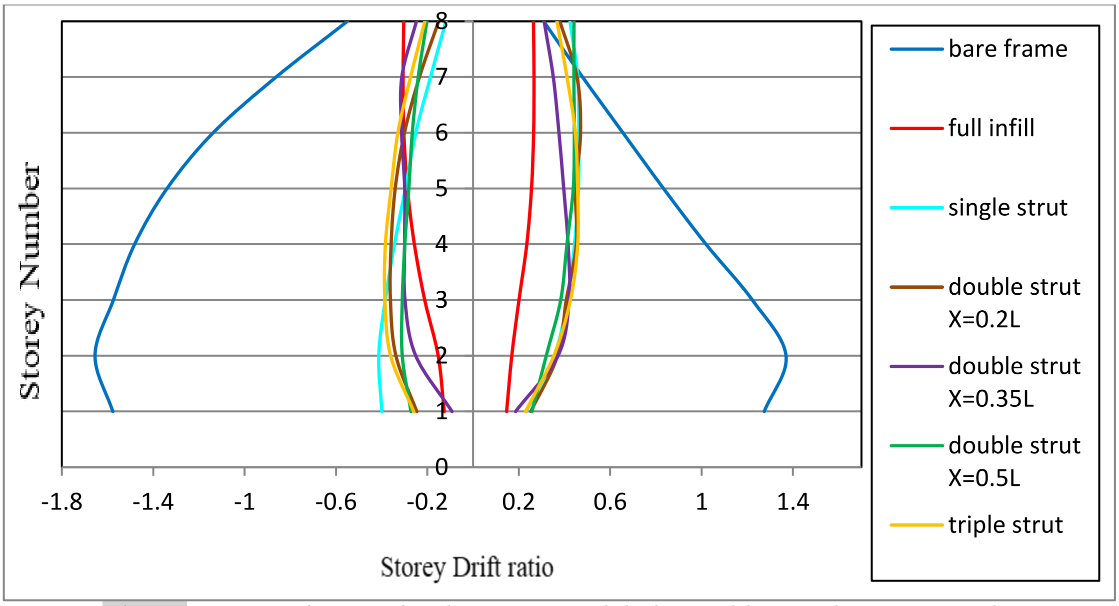

Fig.11 Story Drift Ratio for the Seven Models for Building with 3×6m Panels.

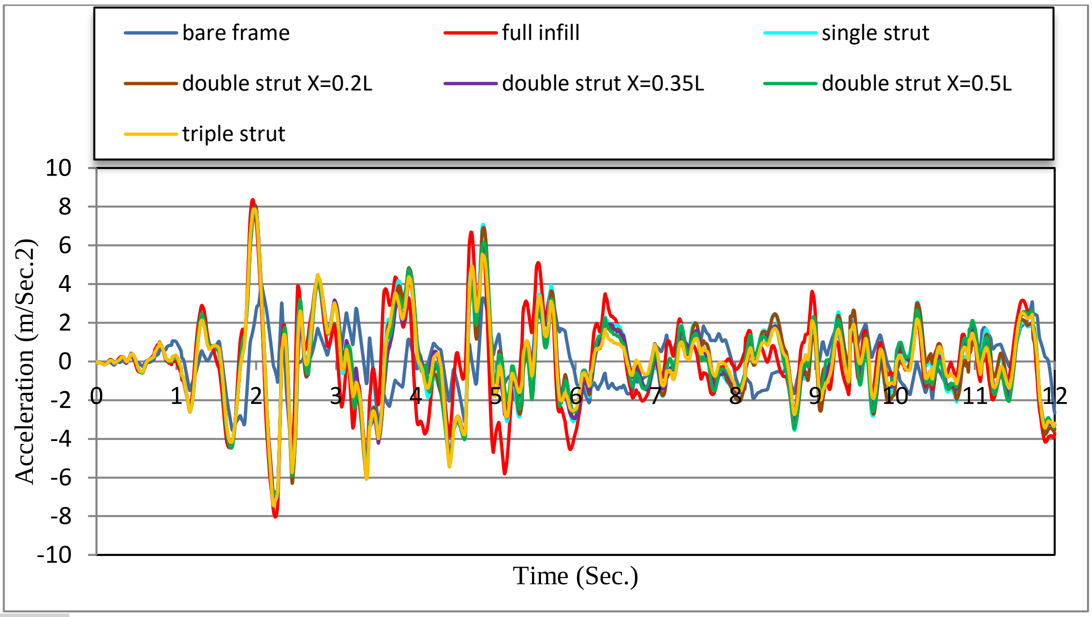

Fig.12 Effect of Including Infill Panels on the Roof Acceleration for Building with 3x3m Panels.

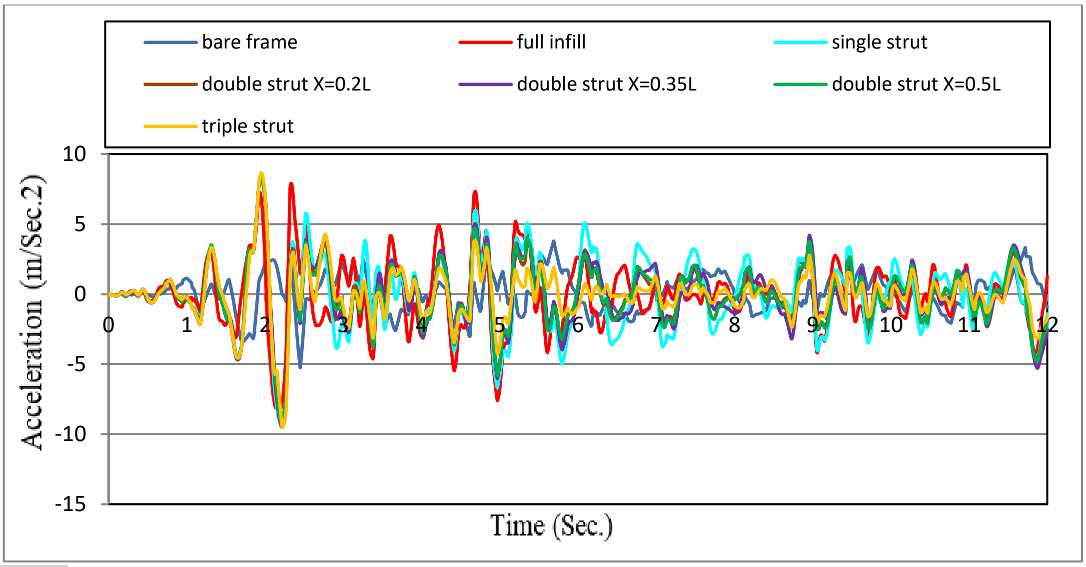

Fig.13 Effect of Including Infill Panels on the Roof Acceleration for Building with 3x5m Panels.

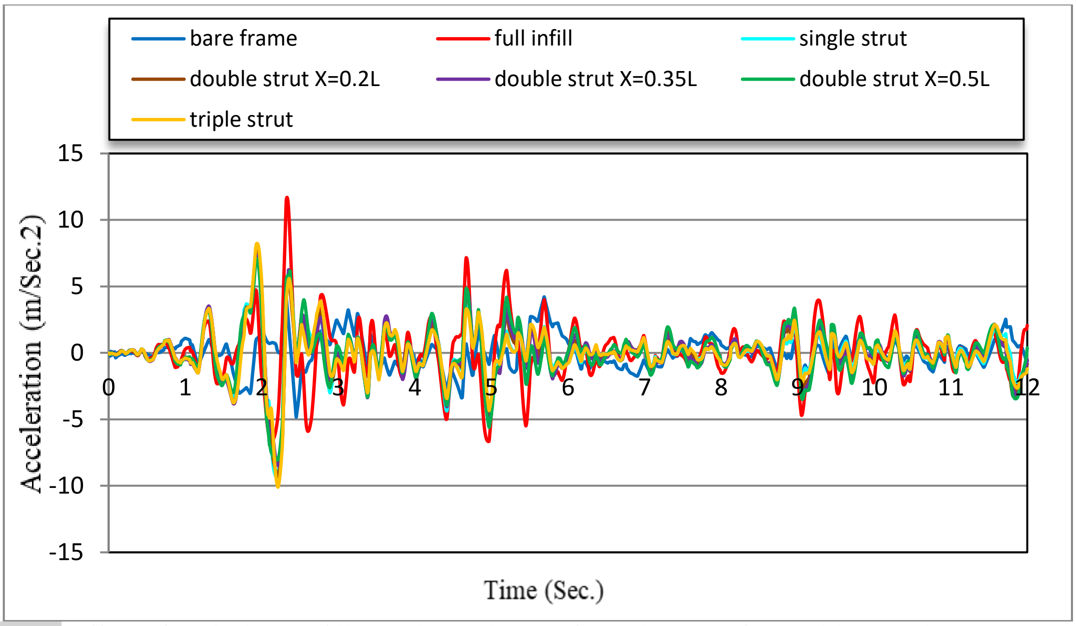

Fig.14 Effect of Including Infill Panels on the Roof Acceleration for Building with 3x6m Panels.

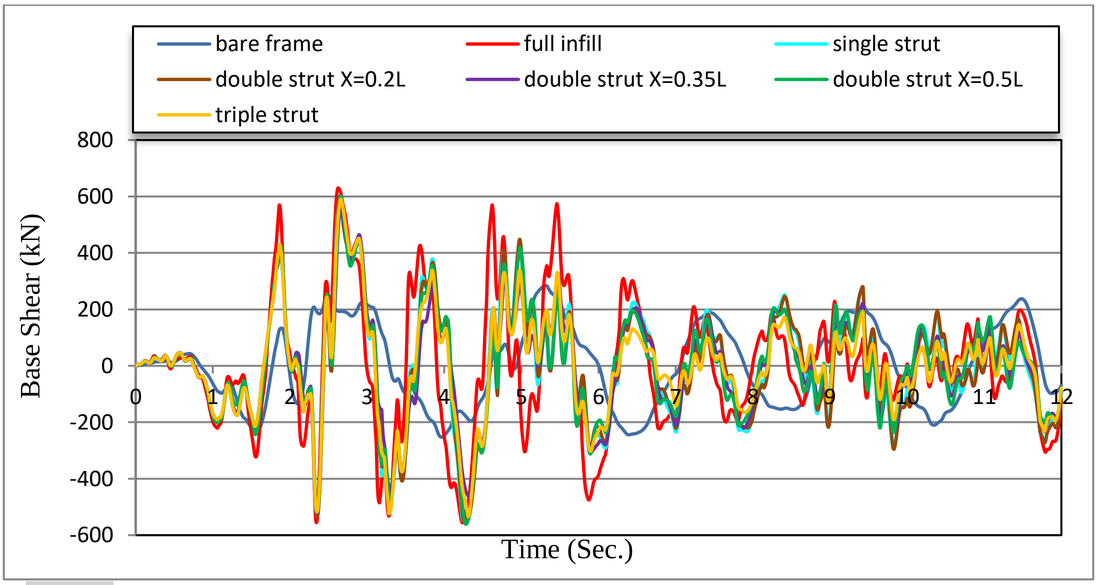

Fig.15 Effect of Including Infill Panels on the Base Shear for Building with 3x3m Panels.

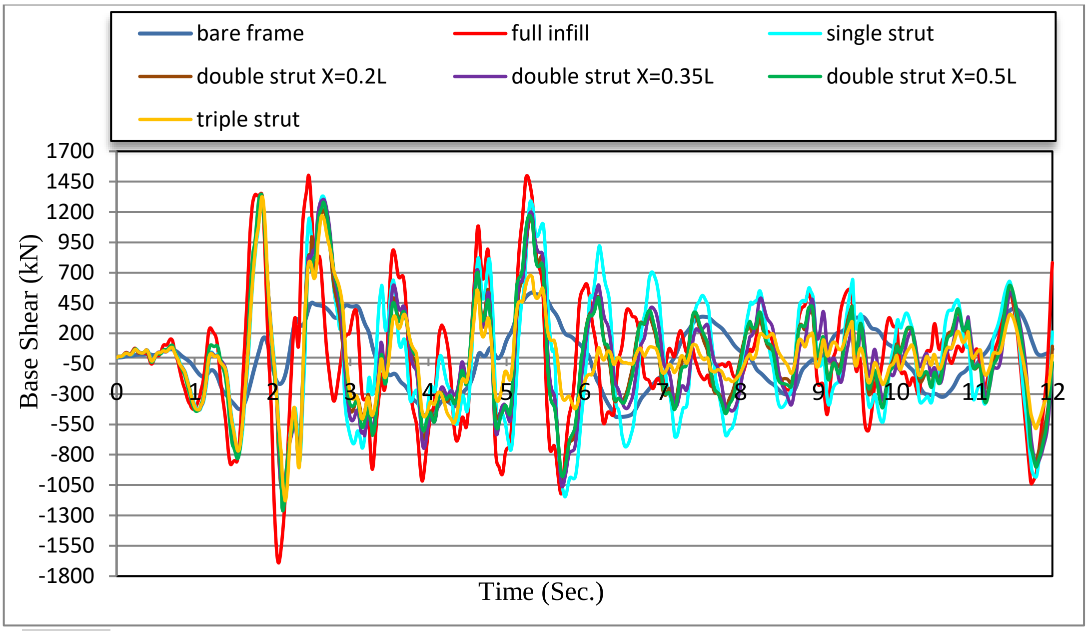

Fig.16 Effect of Including Infill Panels on the Base Shear for Building with 3x5m Panels.

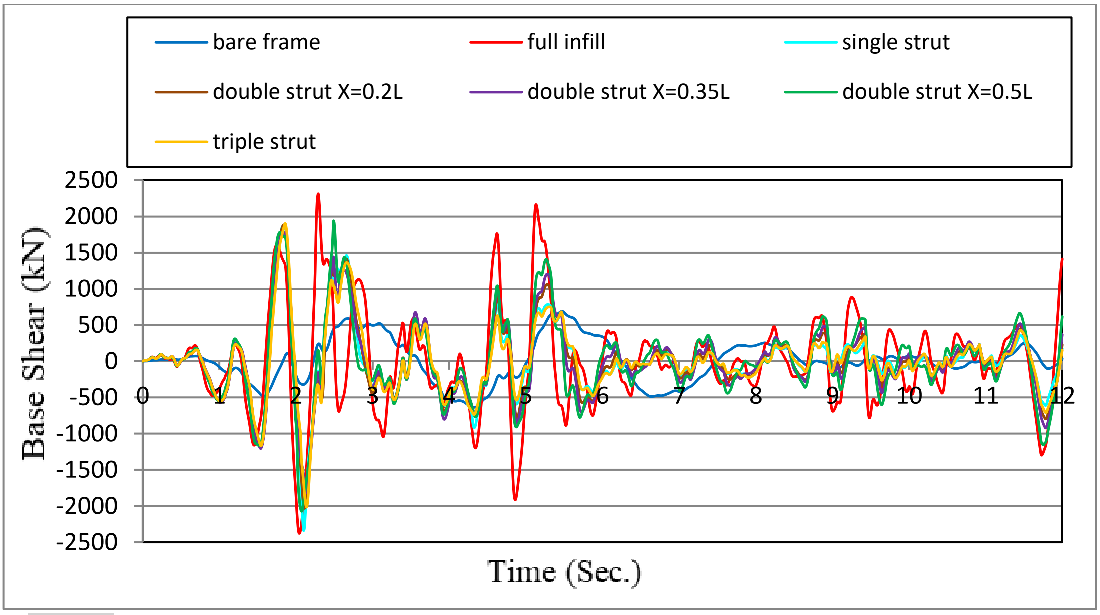

Fig.17 Effect of Including Infill Panels on the Base Shear for Building with 3x6m Panels.

6.CONCLUSIONS

The following conclusions can be drawn from a non-linear dynamic analysis of the effects of earthquakes on hypothetical RC multistory buildings to ascertain the effects of infill panels.

i. Regardless of the modeling method used for these panels, including them in the analysis of these buildings reduced the natural period, lateral roof displacement, and story drift ratio along the structure's height. The percentage of these reductions was higher for constructions with a wider span than the bare frame. The improved lateral stiffness of the buildings brought on by the inclusion of those panels and the enhancement in the dampening of the buildings caused these reductions in roof displacements and story drift ratios .

ii. Contrary to the increase in the parameters mentioned above, when infill panels were included in the analysis compared to the bare frame, the results showed an increase in positive and negative roof acceleration and shear at the base of the building. Therefore, neglecting the infill panels in the analysis of RC buildings subjected to an earthquake effect will result in an underestimation of the shear forces at the base of the building and in the ground floor columns.

iii. It can be concluded that the triple strut and double strut models with X=0.5L were the most suitable simplified representations of infill panels by the strut model because they produced closer outcomes to those of the full infill model.

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