HARRAN ÜNİVERSİTESİ MÜHENDİSLİK DERGİSİ

HARRAN UNIVERSITY JOURNAL OF ENGINEERING

e-ISSN: 2528-8733 (ONLINE)

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Dolgu Duvar Kalınlığı ve Düzeninin Betonarme Çerçevelerin Sismik Performansına Etkisi

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Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): Akcan E., Güneyisi E.M., “Effects of infill wall thickness and arrangement on the seismic performance of the reinforced concrete frames”, ***Harran Üniversitesi Mühendislik Dergisi***, 9(2): 58-70, (2024).

DOI: 10.46578/humder.1483849

HRU Muh Der, 9(2): 58-70 (2024)

Harran Üniversitesi
Mühendislik Dergisi

Araştırma Makalesi

Effects of Infill Wall Thickness and Arrangement on the Seismic Performance of the Reinforced Concrete Frames

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Makale Bilgisi

Başvuru: 14/05/2024
Yayın: 30/08/2024

Keywords

Infill wall
Equivalent diagonal compression strut
Reinforced concrete frames
Nonlinear static analysis

Anahtar Kelimeler

Dolgu duvar
Eşdeğer diagonal basınç çubuğu
Betonarme çerçeveler
Lineer olmayan statik analiz

Abstract

In this study, it is aimed to investigate the seismic behavior of the reinforced concrete (RC) frames with and without infill walls having different thickness and arrangement. To this, 3, 4, 5, 6, and 7 story RC frames consisting of 4 and 5 bays were studied. Infill walls were introduced into the frame models by considering four different arrangements over the height of the structure such as full infill frame (FIF), full infill frame with soft story (FI-SSF), exterior bay infill frame (EBIF), and exterior bay infill frame with soft story (EBI-SSF). For each case, four different infill wall thicknesses of 10 to 25 cm were taken into account. Thus, a total of 170 different 2D frame models with and without infill walls were investigated thorough nonlinear static analysis method by means of SAP 2000 program. The infill panels were modeled by utilizing equivalent diagonal compression strut. As a result of the analyses, the capacity curves of the structures, maximum base shear force, initial stiffness, and mechanism of the plastic hinge formation in the structures were determined and comparatively discussed. It was observed that both wall thickness and arrangement have significant impact on the lateral load carrying capacity and hinge formation of the case studied structures, on the other hand, with their compatible choice the greatest seismic performance could be achieved.

Dolgu Duvar Kalınlığı ve Düzeninin Betonarme Çerçevelerin Sismik Performansına Etkisi

Öz

Bu çalışmada, farklı kalınlık ve düzenlemeye sahip dolgu duvarlı ve duvarsız betonarme çerçevelerin sismik davranışının araştırılması amaçlanmaktadır. Bunun için 4 ve 5 açıklıktan oluşan 3, 4, 5, 6 ve 7 katlı betonarme çerçeveler incelenmiştir. Dolgu duvarlar, yapı yüksekliği boyunca tam dolgulu çerçeve, yumuşak katlı tam dolgulu çerçeve, dış açıklıklarda dolgulu çerçeve ve yumuşak katlı dış açıklıklarda dolgulu çerçeve olmak üzere dört farklı düzenleme dikkate alınarak çerçeve modelleri oluşturulmuştur. Her bir durum için 10 ile 25 cm arasında değişen dört farklı dolgu duvar kalınlığı dikkate alınmıştır. Böylece SAP 2000 programı kullanılarak dolgu duvarlı ve duvarsız olmak üzere toplam 170 farklı iki boyutlu çerçeve modeli doğrusal olmayan statik analiz yöntemiyle incelenmiştir. Dolgu duvar panelleri eşdeğer diyagonal basınç çubuğu kullanılarak modellenmiştir. Analizler sonucunda yapıların kapasite eğrileri, maksimum taban kesme kuvveti, başlangıç rijitliği ve yapılarda plastik mafsal oluşum mekanizması belirlenerek karşılaştırmalı olarak sonuçlar irdelenmiştir. İncelenen yapıların hem duvar kalınlığının hem de çerçeve içerisindeki düzeninin yanal yük taşıma kapasitesi ve mafsal oluşumu üzerinde önemli etkiye sahip olduğu, diğer taraftan bu parametrelerin uyumlu seçimi ile en yüksek sismik performansın elde edilebildiği görülmüştür.

1. INTRODUCTION (GİRİŞ)

A filled framework constitutes a composite structure composed of either reinforced concrete or steel which is packed with concrete or masonry panels to cover the flat rectangle spaces between the top and bottom beams and lateral columns [1]. Within this combined arrangement, masonry function as the material for the external non-bearing walls or separation of the space. Infill walls are often seen as non-load bearing elements within the constructional framework at the design course [2]. The seismic performance of

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reinforced concrete framework with infill wall is often positively influenced by existence of infill walls. Non-structural walls of masonry could increase the structure's overall strength and stiffness. Inversely, undesirable results could take place for instance torsional affects due to in-plan deficiencies and soft story affects due to inconsistencies and repercussion of short-column [3].

Several tools for modelling are being employed for investigating infilled frames. These tools for modelling could be separated into three main classifications [4-6]:

(a) Micro-models or local ones

(b) Macro-models or simple ones

(c) Discrete (mesoscale) ones.

Due to its computational efficiency and reliance on structural mechanical data acquired from masonry infill wall tests, macro modeling provides several advantages [7]. This category uses basic models that depend on observational understanding of the action of the infill wall. An instance of a typical macro-model for infilled panels equivalent diagonal compression strut [8]. One of the oldest analytical researches utilizing elastic theory was executed by Polyakov [9]. Based on his study and investigations on masonry panels subjected to compression in a diagonal manner, he claimed that the masonry walls in infilled framework facing lateral loads could have a similar impact as a diagonal strut as represented in Figure 1 [10].

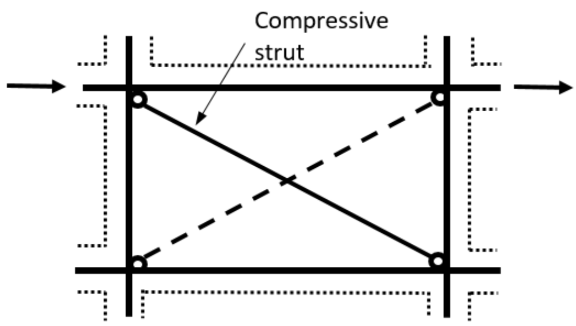


Figure 1. *Model for infilled frames with a diagonal strut [10]*

In many situation, the geometry of micro-models using the finite elements approach takes more activity, power and time in comparison of equivalent diagonal strut methods [11]. The strength and stiffness of the intricate framework were discovered to be greatly influenced by the inclusion of masonry infill wall [12-13]. Soft-story columns experience damage when the structure's lateral stiffness immediately shifts, diminishing their ability to bear a lateral load when the structure frame with a soft-story [14]. In addition, based on investigations, the placement of partial openings inside an infill wall provide an enormous influence on the lateral stiffness of the frame. Openings arranged in which the load transfer of the infill wall commences have a major influence on the stiffness of the structural frame. On the other hand, openings that are positioned at the side of little load transmission moderately diminish the stiffness of the structural frame [15].

In the literature it is reported that if an infill panel integrated with the frame is subjected to a lateral load, it encounters a distinct split from the surrounding frame, predominantly along the length of the connection. In this case, the interface region is decreased to only two adjacent compression edges at the ends that keep going in a diagonal contact. Because of this behavior, it has been expected that the infill performs identically to a diagonal strut bracing which in turn an equivalent frame as illustrated in Figure 2 [16]. The infill walls normally have a favorable influence on the seismic action of buildings when they are properly considered in the design and also properly located along the structural frame. But, inconsistent placement of the infill walls especially through the elevation of the building may result in adverse consequences [17].

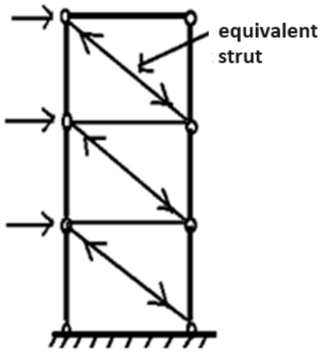


Figure 2 *Equivalent frame representation having infill panels [16]*

In this work, the effects of infill wall thickness and arrangement over the structure height on the seismic behavior of the reinforced concrete frames were investigated. The 3 to 7 story reinforced concrete frames with 4 and 5 bays were studied. Four different infill wall arrangements, namely, full infill frame (FIF), full infill frame with soft story (FI-SSF), exterior bay infill frame (EBIF), and exterior bay infill frame with soft story (EBI-SSF) were considered together with four different infill wall thicknesses of 10, 15, 20 and to 25 cm. Thus, various frame models with and without infill walls were examined by nonlinear static analysis. The capacity curves, maximum base shear, initial stiffness, and plastic hinge formation in the structures were evaluated and discussed.

2. METHODOLOGY (METODOLOJİ)

The purpose of this study is to examine the performance of the reinforced concrete frames with and without infill walls under applied lateral loads. For this, reinforced concrete frames with 3, 4, 5, 6, and 7 storey levels, each consisting of 4 and 5 spans, are formed. The height of each floor is taken as 3 m and each span interval is 5 m. For these created reinforced concrete frames, infill walls with four different thicknesses (t_w =10 cm, t_w =15 cm, t_w =20 cm, t_w = 25 cm) were modeled. Additionally, different arrangements of these infill walls such as full infill frame (FIF), full infill frame with soft story (FI-SSF), exterior bay infill frame (EBIF), and exterior bay infill frame with soft story (EBI-SSF) on the reinforced concrete frames were created, as shown on an example frame in Figure 3. The nonlinear static analysis was conducted on all frame models (totally 170 frame models with and without infill walls) using the SAP2000 program.

The concrete grade used in this study is C30/37, and the reinforcement steel is S420. The vertical load applied to the frames are 12 kN/m for dead load and 8.5 kN/m for live load. The column sections used in the frames are 60x60 cm, 55x55 cm, 45x45 cm, and 30x30 cm which varied over the elevation of the frames. All beam sections of the frames are 30x60 cm. The typical code designed frames are used. Columns and beams were modeled as frame elements. For the nonlinear static or the pushover analysis, the analytical models of the frames were developed by taking into account lumped plasticity modelling approach. The frames were subjected to gradually increasing lateral loads which were determined based on the first mode of vibration behavior of the frames. For the lumped plasticity modelling, the columns hinges based on axial load moment interaction behavior (PMM), the beam hinges based on the moment (M3), the infill walls hinges based on the axial load (P) were utilized. Furthermore, in the lumped plasticity approach, the plastic hinges were assigned to the both ends of the column and beam members outside the beam column connection rigid zone. In modelling of the hinges formed in the infill walls, a macro-model approach was adopted, and the infill walls were modeled as equivalent diagonal strut, as seen in Figure 4. The plastic hinges were defined at the midpoint of each equivalent diagonal strut member, for modelling the nonlinear behavior of the infill wall panels.

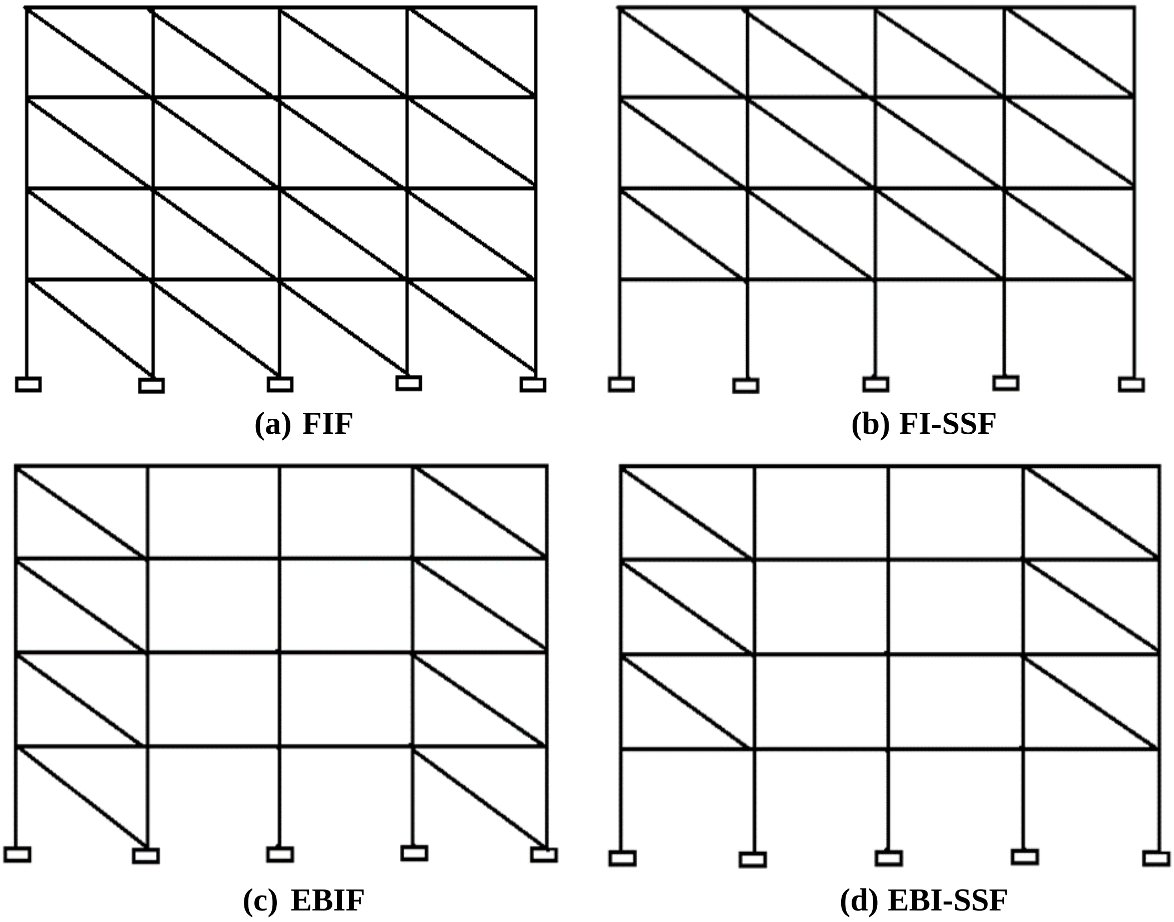


Figure 3. *An example model of different arrangements of infill walls for 4 storey-4 bay frames*

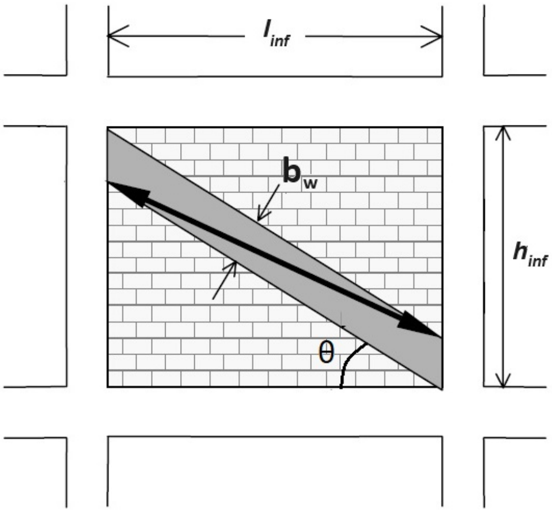


Figure 4. *Strut placement in the frame model [18]*

In the literature, it is known that one, two, or multiple numbered struts can be used to model infill walls. Infill wall width is one of the important parameters considered in the literature. It can be seen that many researchers have developed different formulas for infill wall width. In this study, for infill wall width (b_w), the equation (1) suggested by FEMA (1998) [19] was considered.

$$b_w = 0.175d(\lambda_h H_w)^{-0.4} \quad (1)$$

Here, *d* is the diagonal length of strut for modelling infill panel, H_w is the height of the column determined between the center of the beams, λ_h is a unitless factor for representing the relative stiffness of the infill wall to the frame which is dependent on height of infill panel, modulus of elasticity of frame material and infill material, moment of inertia of the column, thickness of the infill wall and the slope of the equivalent strut. One of the properties that need to be considered in infill walls is their mechanical properties. In this study, the mechanical properties of the infill walls were obtained from the experimental studies conducted by some previous researches [20, 21]. Accordingly, elastic modulus, shear modulus, and tensile strength of the infill wall are as follows: E_w=1495 MPa, G_w=598 MPa, and f_{tp}=0.36 MPa. Among various studies available in the literature to determine the strength and stiffness of the infill wall, the study of Panagiotakos and Fardis [22] is used. In the study of Panagiotakos and Fardis [22], the force displacement graph which is based on the initial shear stiffness of the infill wall (K_1), yielding force corresponds to crack initiation in the infill panel (F_y), displacement corresponds to yield force (S_y), equivalent strut's axial stiffness (K_2), peak force carried by the infill panel (F_m), the displacement corresponds to peak force (S_m), residual force that can be carried by the infill (F_m), the displacement corresponds to residual force (S_r), are obtained as given below (Eqns 2-9).

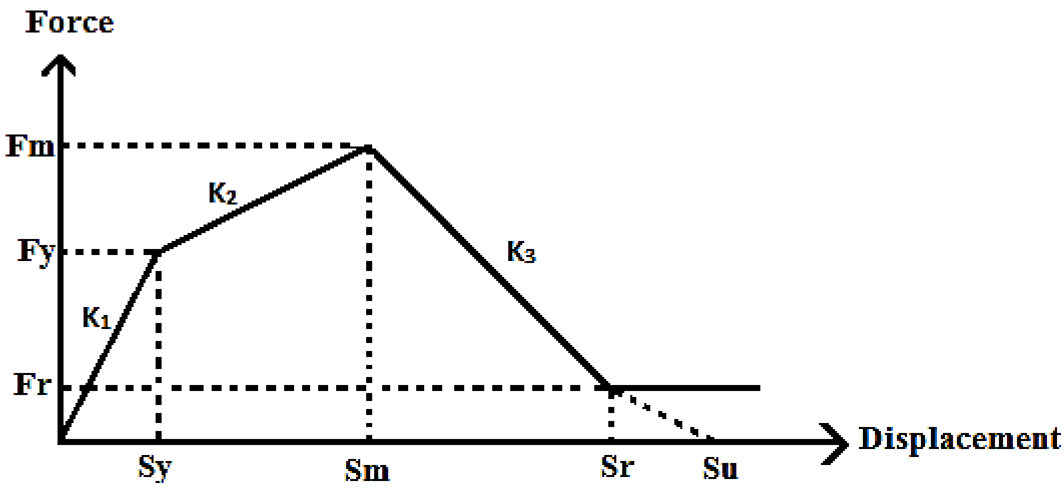


Figure 5. *Force-displacement curve for equivalent strut model suggested by [22]*

Initial shear stiffness K_1 of the un-cracked panel:

$$K_1 = \frac{G_w t_w L_w}{H_w} \tag{2}$$

Yielding Force F_y corresponding to the first cracking of the panel:

$$F_y = f_{tp} t_w L_w \tag{3}$$

Displacement at the yielding point, S_y

$$S_y = \frac{F_y}{K_1} \tag{4}$$

Axial stiffness K_2 of the equivalent strut:

$$K_2 = \frac{E_m b_w t_w}{d} \tag{5}$$

Displacement at the maximum force point, S_m:

$$S_m = S_y + \frac{F_m - F_y}{K_2} \tag{6}$$

Assuming the ratio between the yield force and maximum force:

$$\frac{F_y}{F_m} = 0.6 \tag{7}$$

F_r, residual force:

$$F_r = 0 \tag{8}$$

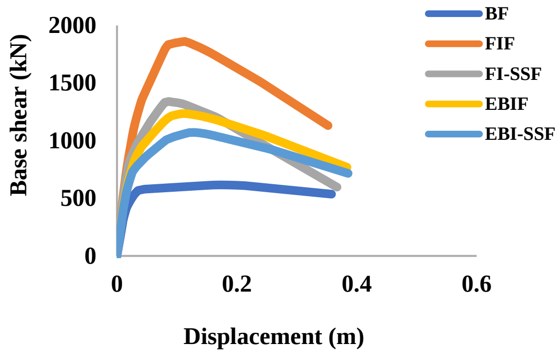
The proportion of the last displacement to the maximum displacement:

$$\frac{S_r}{S_m} = 5 \tag{9}$$

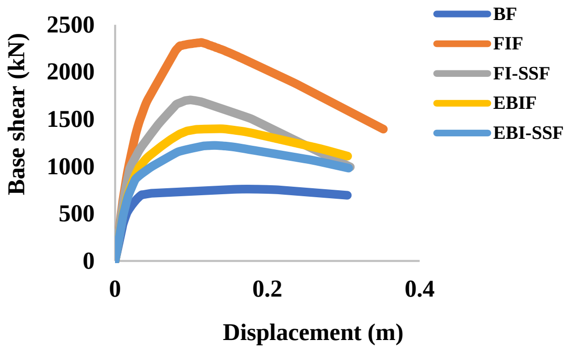
In these equations G_w, f_{tp} and L_w are the shear modulus, tensile strength and length of the infill panel, respectively.

4. RESULTS AND DISSCUSSION (SONUÇLAR VE TARTIŞMA)

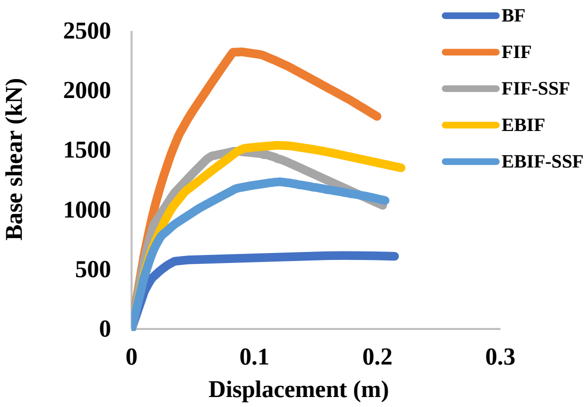
The lateral behavior of the bare frames (BFs) and the frames with four different infill wall arrangements (full infill frame (FIF), full infill frame with soft story (FI-SSF), exterior bay infill frame (EBIF), and exterior bay infill frame with soft story (EBI-SSF)) and four different infill wall thicknesses (t_w) of 10, 15, 20 and to 25 cm are analyzed. In Figure 6, the load carrying capacity curves of 4 story-4 and 5 bay frames with and without infill walls are illustrated. As seen in Figure 6, the existence of infill walls in the structures increases both the strength and stiffness values. Moreover, it is observed that as the thickness of infill wall increases, the structures exhibit greater stiffness and strength. For example, the bare frame's maximum base shear is roughly 616 kN considering 4 story-4 bay frames, whilst the maximum base shear of the full infilled frame having 10 cm, 15 cm, 20 cm, 25 cm wall thickness are obtained as approximately 1862 kN, 2324 kN, 2850 kN, 3364 kN, respectively. Besides, for the infill frame which has 10 cm infill wall thickness, the capacity of lateral load carrying is measured as roughly 3.0 times greater than that of the bare frame. For the infill frame which has 15 cm infill wall thickness, the capacity of lateral load carrying is roughly 3.8 times greater than that of the bare frame. For the infill frame which has 20 cm infill wall thickness, the capacity of lateral load carrying is about 4.6 times higher than that of the bare frame. On the other hand, for the infill frame having 25 cm infill wall thickness, the capacity of lateral load carrying is observed as 5.5 times greater than that of the bare frame. These findings could be associated with the increase in area of contact between the reinforced concrete frames and infill wall. Additionally, higher strength and stiffness values are observed with the increment in the number of bays of the frames. The stiffness of the frame diminishes as the number of infill walls decreases. In all graphs, FIF shows greater stiffness and strength compared to the bare frames and the frames with different arrangements of infill walls. Because of the soft story, FI-SSF has less strength than FIF. The strength of EBIF is greater than that of the EBI-SSF, and similarly FIF is greater than that of FI-SSF.



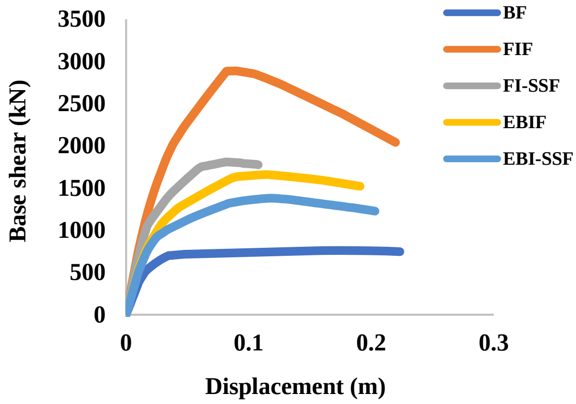
(a) 4-story 4-bay t_w=10 cm



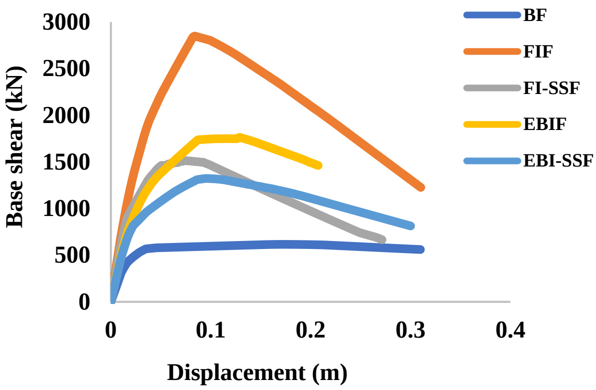
(b) 4- story 5-bay t_w=10 cm



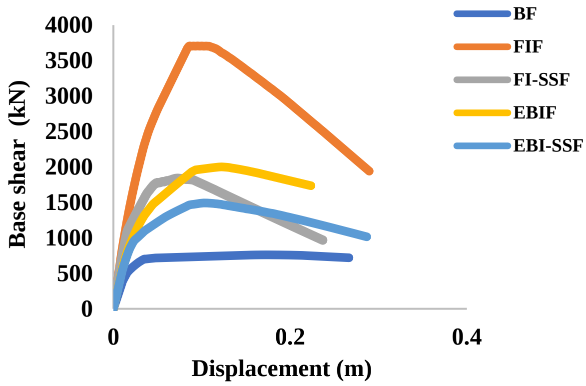
(c) 4- story 4-bay t_w=15 cm



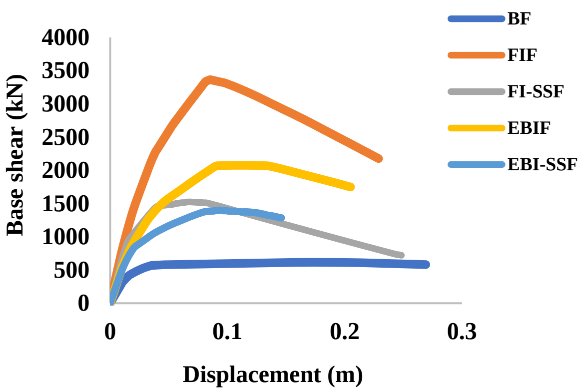
(d) 4- story 5-bay t_w=15 cm



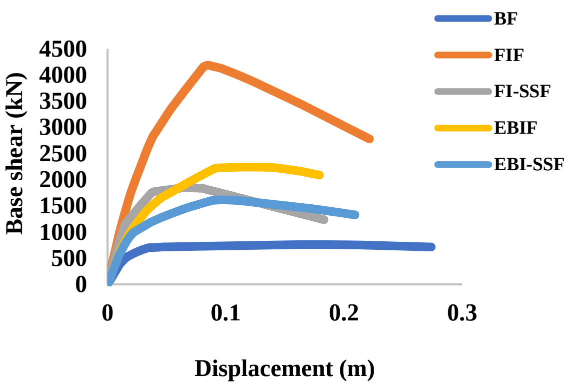
(e) 4- story 4-bay t_w=20 cm



(f) 4- story 5-bay t_w=20 cm



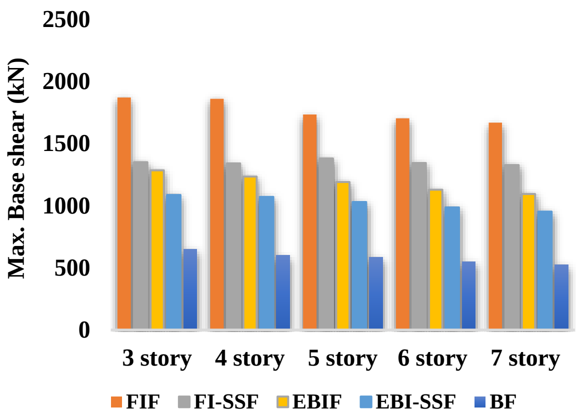
(g) 4- story 4-bay t_w=25 cm



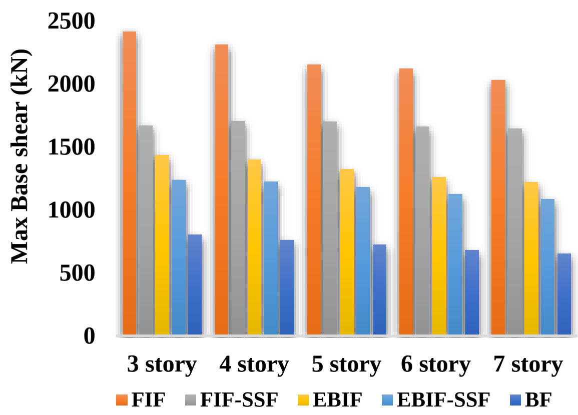
(h) 4- story 5-bay t_w=25 cm

Figure 6. *Comparison of the lateral load carrying capacity curves of 4 story frames with and without infill walls*

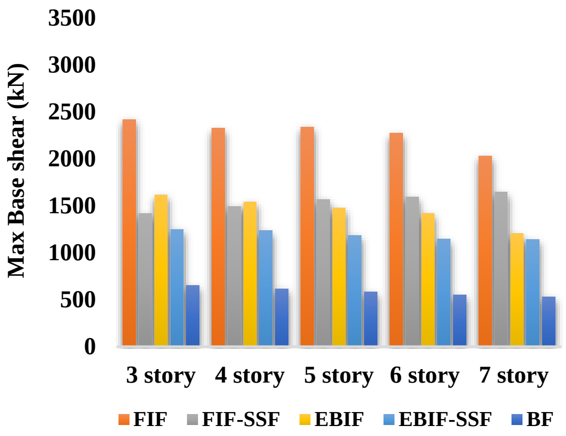
In Figure 7, the maximum base shear variation of 3, 4, 5, 6, and 7 story bare frames with 4 and 5 bays and those with infill walls having various properties are given. It is pointed out that as the thickness of infill wall increases, the maximum base shear values has a tendency to rise. This increment is more noticeable for the case of FIF. Additionally, as number of bays of frames increases the maximum base shear values increase due to the improved resistance to larger lateral stresses and this difference is more evident for the FIF. For instance, for the full-infilled frame with 10 cm infill panel thickness, the maximum base shear for 4 story-4 bay frame is roughly 1862 kN while for 4 story-5 bay frame is about 2313 kN. For the full-infilled frame with 15 cm infill panel thickness, the maximum base shear for 4 story-4 bay frame is nearly 2324 kN while for 4 story-5 bay frame it is almost 2889 kN. For the full-infilled frame with 20 cm infill panel thickness, the maximum base shear for 4 story-4 bay frame is about 2850 kN while for 4 story-5 bay frame is obtained as 3706 kN. Moreover, for the full-infilled frame with 25 cm infill panel thickness, the maximum base shear for 4 story-4 bay frame is calculated as 3364 kN while for 4 story-5 bay frame is roughly 4189 kN. In all cases, the maximum base shear values of FI-SSF and EBIF generally give close results. Furthermore, as the number of stories increases, the maximum base shear values mostly tend to decrease.



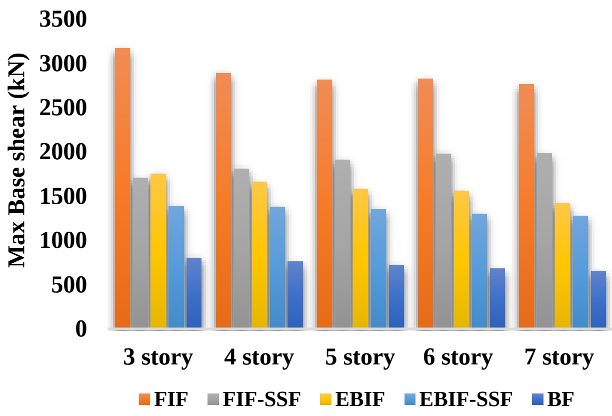
(a) Frames with 4 bay and t_w=10 cm



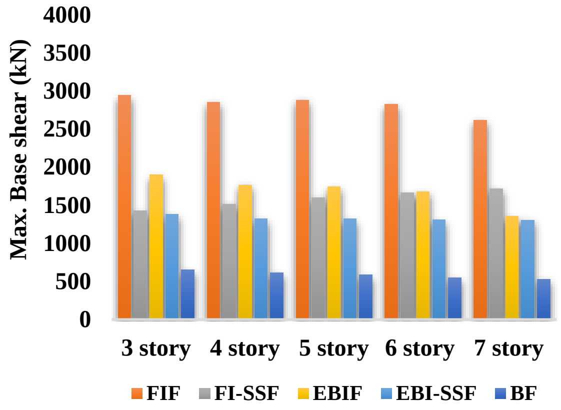
(b) Frames with 5 bay and t_w=10 cm



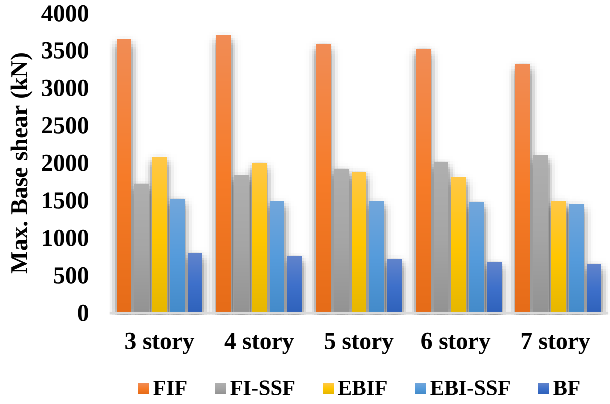
(c) Frames with 4 bay and t_w=15 cm



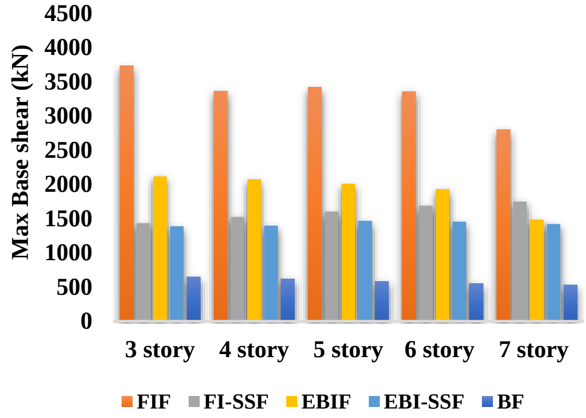
(d) Frames with 5 bay and t_w=15 cm



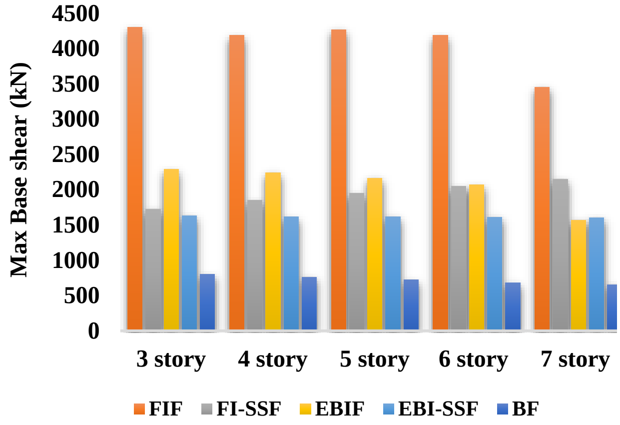
(e) Frames with 4 bay and t_w=20 cm



(f) Frames with 5 bay and t_w=20 cm



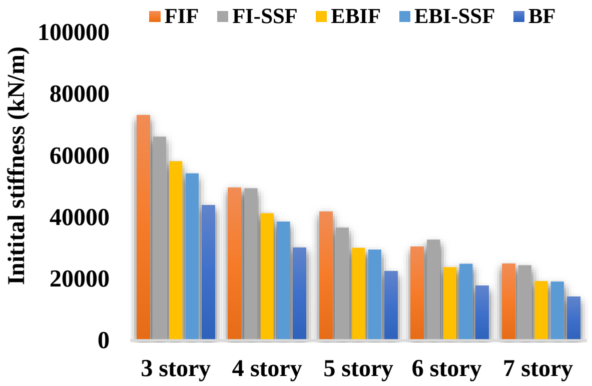
(g) Frames with 4 bay and t_w=25 cm



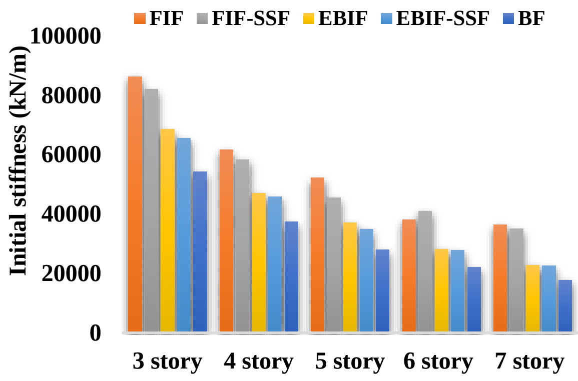
(h) Frames with 5 bay and t_w=25cm

Figure 7. *Maximum base shear variation for 3, 4, 5, 6, and 7 story frames with and without infill walls*

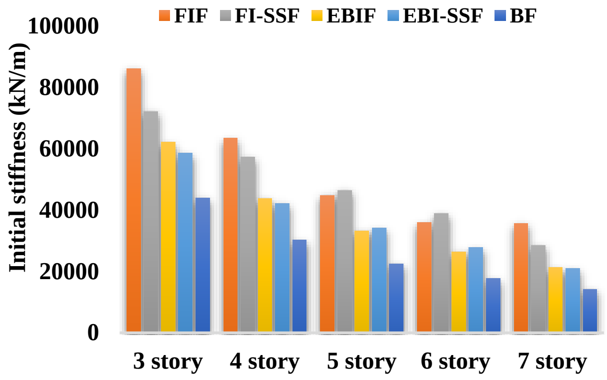
As seen in Figure 8, as the thickness of infill wall increases the initial stiffness values also increase. This increase is more obvious for the FIF. For instance, the full infilled frame's initial stiffness values for with 10 cm, 15 cm, 20 cm, 25 cm infill wall thickness is approximately 49660 kN/m, 63417 kN/m, 73235 kN/m, and 82870 kN/m, respectively, considering 4 story-4 bay frames. Furthermore, as the number of bays of frames rises the initial stiffness values increases and this increment is more obvious for the FIF. For instance, the full infilled frame's initial stiffness values for with 10 cm, 15 cm, 20 cm, 25 cm infill wall thickness is evaluated as 61719 kN/m, 79104 kN/m, 82313 kN/m, and 103545 kN/m, respectively, considering 4 story-5 bay frames. In most cases, as the number of infill panels decrease, the initial stiffness values also decrease. In addition, as the number of stories decreases, the initial stiffness values also decrease. On the other hand, the period of the frames is also affected by the existence of the infill panels, for example, in the study of Koçak and Yıldırım [23], it is pointed out that the infilled building's periods are less than that of the bare building about 10-40 %, based on the wall ratio.



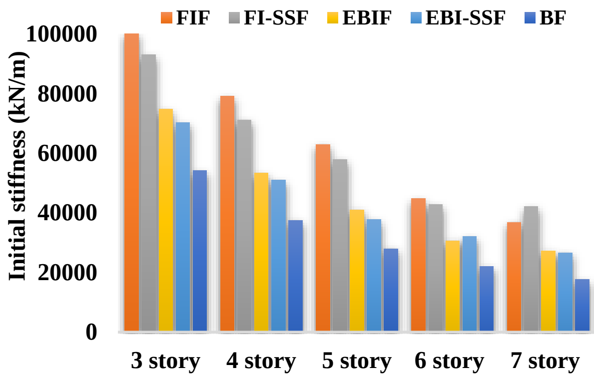
(a) Frames with 4 bay t_w=10 cm



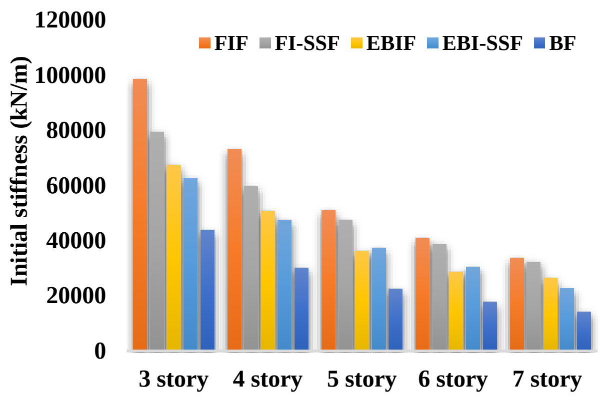
(b) Frames with 5 bay t_w=10 cm



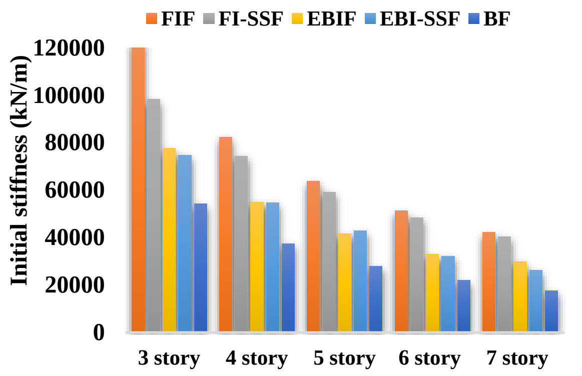
(c) Frames with 4 bay t_w=15 cm



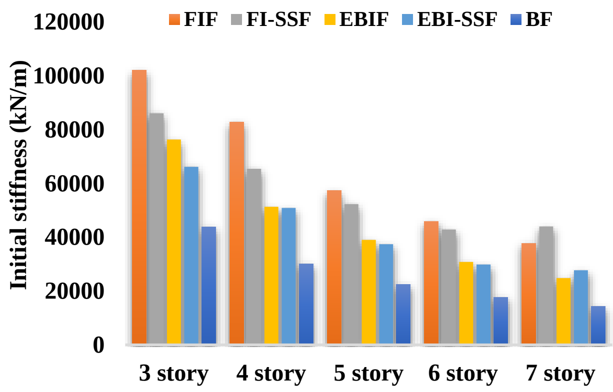
(d) Frames with 5 bay t_w=15 cm



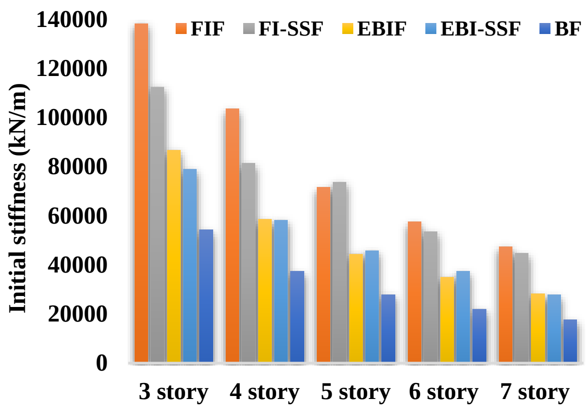
(e) Frames with 4 bay t_w=20 cm



(f) Frames with 5 bay t_w=20 cm



(g) Frames with 4 bay t_w=25 cm



(h) Frames with 5 bay t_w=25 cm

Figure 8. *Initial stiffness variation for 3, 4, 5, 6, and 7 story frames with and without infill walls*

The plastic hinge formation of 3 story-4 bay bare frame and infilled frames having wall thickness of 25 cm at the failure points are illustrated in Figure 9. As shown in Figure 9, a plastic hinge does not form on the columns of the second and third stories in the bare frame, however, at the columns on the first floor and all of the beams the plastic hinges have occurred. In the case of the frames, namely FIF and EBIF, with the contribution of the infill walls, it is observed that especially at the last floors the rotation demand is less than that of the bare frame. However, in the case of the soft story frames, namely FI-SSF and EBI-SSF, the first-floor columns failed.

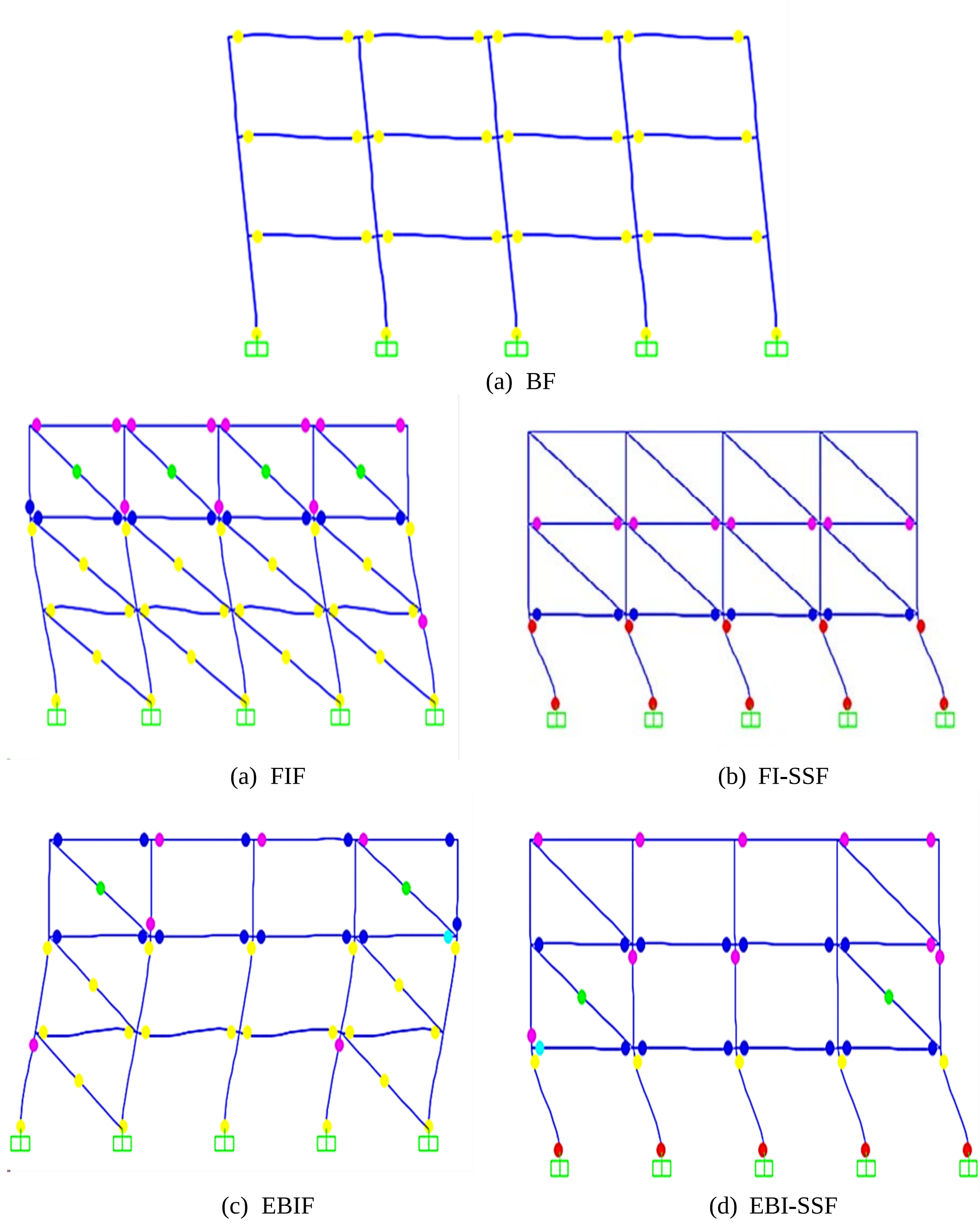


Figure 9. *Plastic hinge distribution of 3 story-4 bay bare frame and infilled frames with t_w=25 cm at failure*

5. CONCLUSIONS (SONUÇLAR)

In accordance with the evaluations and findings mentioned above, the following conclusions could be made;

- The analysis of the results indicates that the inclusion of the infill walls in modelling provide reinforced concrete frames more strength and stiffness than the bare frame, irrespective of the infill wall thicknesses considered in this study.
- The arrangement of the infill walls over the frame elevation has considerable effect on the seismic response of the case study structures. Among the cases with infill walls, full infilled frame has the highest lateral load carrying capacity and stiffness. The worst case is observed for the exterior bay infill frame with soft story having the lowest lateral load capacity and stiffness. On the other hand, when the thickness of infill wall rises from 10 cm to 25 cm, the lateral load carrying capacity of all frame types increases because of the wall contribution.
- Mainly for the infill wall frames with soft story, the plastic hinge distribution for the first story columns become worse and they reach the failure state. Similarly, their strength and stiffness is lower than that without soft story.

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