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Research Article

Investigating the effect of infill walls on steel frame structures

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A B S T R A C T

Infill walls consisting of materials such as hollow concrete, hollow clay and autoclaved aerated concrete bricks are not only preferred in reinforced concrete buildings but also in steel frame structures. It is a well-known fact that infill walls limit the displacement of frames under horizontal loads. However, they may also bring about certain problems due to being placed randomly in horizontal and discontinuously in vertical directions for some architectural reasons. Moreover, cracks in frame-wall joints are observed in steel frame structures in which ductile behaving steel and brittle behaving infill walls are used together. In this study, the effect of infill walls on steel frames has been investigated. In the steel frame structure chosen for the study, four different situations consisting of different combinations of infill walls have been modeled by using ETABS Software. Later, the pushover analyses have been performed for all the models and their results have been compared. As a result of the analyses done by using the equivalent diagonal strut model, it has been found out that infill walls limit the displacement of steel frames and increase the performance of a structure. However, it has been also determined that in the steel frame structure in which the infill walls have been placed discontinuously in vertical and asymmetrically in horizontal, infill walls may lead to torsional and soft story irregularities. As a result, it is possible to observe cracks in the joints of infill walls and steel frame, the deformation properties of which differ, unless necessary precautions are taken.

A R T I C L E   I N F O

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1. Introduction

Infill walls which are widely used in reinforced concrete (RC) buildings are also preferred commonly in steel frame structures for certain architectural reasons. Thus, it is crucial to understand the effect of brittle behaving infill walls between steel frames which show ductile behavior. Infill walls are non-structural elements and they consist of materials such as hollow concrete, clay and autoclaved aerated concrete (AAC) bricks whose raw materials are aggregate, pumice, clay, basaltic pumice, cement, lime and gypsum. Therefore, the effect of infill walls on the structural behavior is ignored and they are only taken into account as dead load in analyses. However, analytical and experimental studies have revealed that infill walls decrease story drift against horizontal loads, provide strength and stiffness to a structure, and thus all this effect cannot be ignored (Kaplan, 2008; İrtem et al., 2005; Beklen and Çağatay, 2009; Sevil et al., 2010; Beklen, 2009; Mehrabi et al., 1996; Murty and Jain, 2000). Yet, along with the contributions of infill walls stated above, there are also other studies available showings that they affect the behavior of a structure in a negative way (Akkuzu, 2007; Yadollahi et al., 2016). The design choices, such as using infill walls only in one axis of a structure, changing the area and position between stories of infill walls (Figs. 1a-b), forming ribbon windows (Figs. 1c-d), might cause torsion, soft story and formation of short column. As a result of the brittle structure of infill wall materials, the compressive stress formed in the corners leads to crushing and local loss of strength. Fig. 2 demonstrates that when the infill walls of the structure whose basement is surrounded with window walls from two sides and with infill walls from the other two sides have been analyzed, torsion in the structure has been determined (Doğan and Bakırcı Er, 2011).

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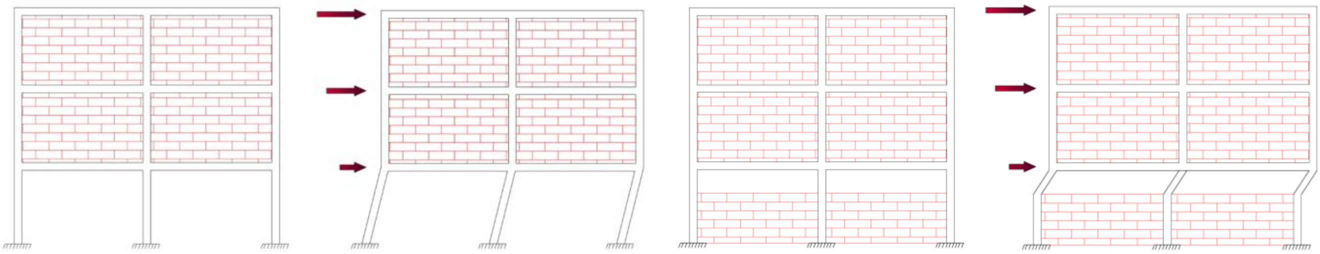
While such vertical discontinuity of infill walls increases the stiffness of frames on upper stories, it may lead to excessive stress in structural elements of the basement (Tabeshpour et al., 2012; Murty and Jain, 2000; Anıl and Altın, 2007).

The number of steel structures has been increasing by the reason of its ductile behavior, energy absorbing capacity, fast manufacture, and its being recyclable, environment-friendly and light. They are also economical systems considering that they do not require formwork and scaffolding, they weigh much less, and they can be built in any weather and in less time. In steel frame systems, various partition systems are used in order to meet the need of partitions in the structure (Fig. 3).



(a) (b) (c) (d)

Fig. 1. (a) The basement of the structure without infill walls; (b) The behavior of the structure without infill at basement under horizontal load; (c) Ribbon window; (d) The formation of short column under horizontal load.

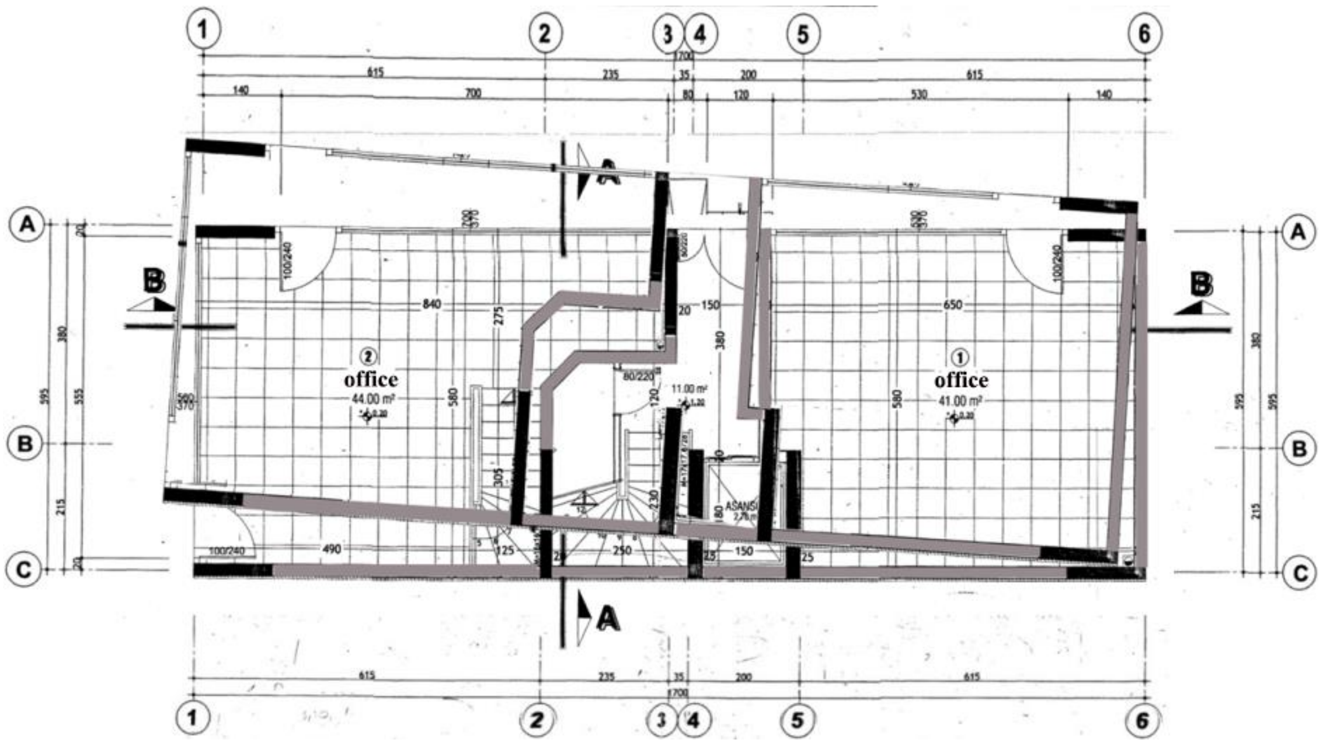


Fig. 2. Basement plan and possible torsion.

(a) (b) (c) (d)

Fig. 3. Steel frame infills: (a) Light section steel and panel; (b) Hollow concrete brick; (c) AAC; (d) Hollow clay brick.

Similar to RC buildings, hollow concrete brick, hollow clay bricks and AAC are used as infill wall material in steel structures. In the experimental studies investigating the effect of infill walls on steel frame systems, as it is in RC buildings, infill walls have been found to increase the horizontal load bearing capacity, lateral stiffness and energy absorbing capacity of the frame system significantly (Kaltakcı et al., 2006; Ghaffarzadeh and Ghalghachi, 2009; Kaymak and Tuna, 2012). However, in almost all these studies, the asymmetrical structure and discontinuity of the infill walls have not been taken into account, yet they have been considered as single span planar frames. Whereas, the behavior of steel structure frames, which are more ductile compared to RC, should be taken into account as three-dimensional with their brittle behaving infill walls. It has been asserted that using steel and infill walls together, which have different mechanical properties, causes cracks in joints (Öktem, 2003). Similarly in Fig. 4, cracks can be seen between the steel frame and the infill wall in finished and unfinished structures. In this study, analyses on a steel structure have been carried out by forming various combinations with infill walls. The effect of infill walls on the structure has been reflected by modeling them with diagonal bars.

Fig. 4. Steel structure under construction and cracks between infill walls and steel frames.

2. The Steel Frame Examined and the Modellings

The steel frame chosen can be seen in Fig. 5a. This frame without infill has been defined as Type 1. Type 2-4, which have been examined to understand asymmetrical effect of infill walls horizontally and vertically, are presented in Fig. 5b-d respectively.

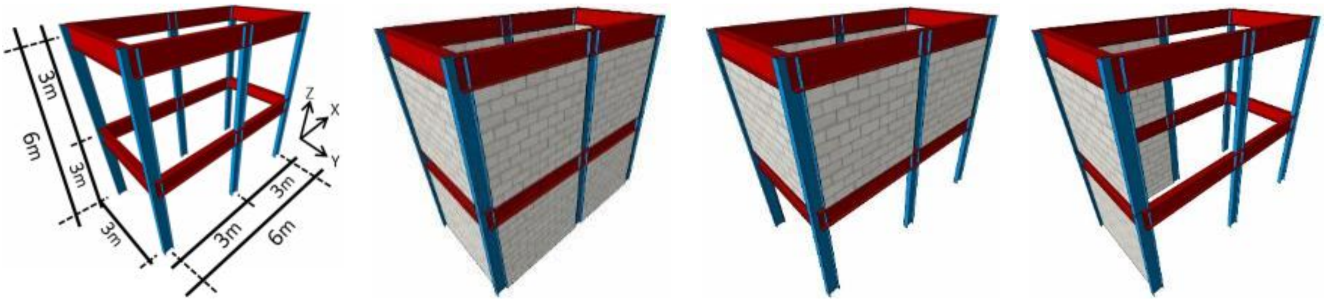
The columns and beams of the steel frame that has been examined are made of an IPE300 steel profile (Fig. 6), and the AAC properties of infill walls are presented in Table 1.

It should not be forgotten that these parameters affect the elasticity module of infill walls and the in-frame strength of infill walls showing different characteristics everywhere cannot be the same, either. Infill walls generate pressure in the column-beam joint region of frame under horizontal loads (Fig. 7). Behavior of infills formulated according to this approach is presented in Eqs. (1) to (3) (FEMA-356, 2000).

$$d = \sqrt{H^2 + L^2}\,, \tag{1}$$

$$W_{ef} = 0{,}175 \times (\lambda \times H)^{-0{,}4} \times d\,, \tag{2}$$

$$\lambda = \sqrt[4]{\frac{E_m \times t \times sin2\theta}{4 \times E_s \times I_c \times h}}\,, \tag{3}$$



(a) (b) (c) (d)

Fig. 5. Steel frames: (a) Type 1; (b) Type 2; (c) Type 3; (d) Type 4.

Table 1. IPE-300 section properties.

IPE 300 Section Properties			AAC Mechanical Properties		
Total Depth	300	mm	Block Dimensions	600x250x120	mm
Top Flange Width	150	mm	Wall Thickness	125	mm
Top Flange Thickness	10.7	mm	Modulus of Elasticity	2250	N/mm^2
Web Thickness	7.1	mm	Poission's Ratio	0.25	
Bottom Flange Width	150	mm	Compressive Strength	3.5	N/mm^2
Bottom Flange Thickness	10.7	mm	Material Strength Class	G3	
Fillet Radius	15	mm	Unit Weight	600	kg/m^3

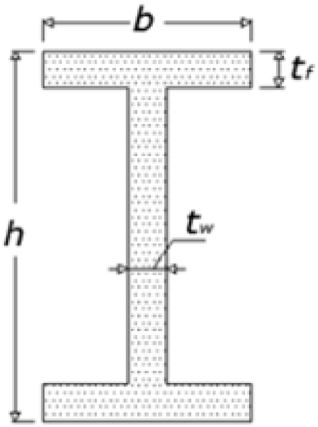


Fig. 6. IPE300 Section.

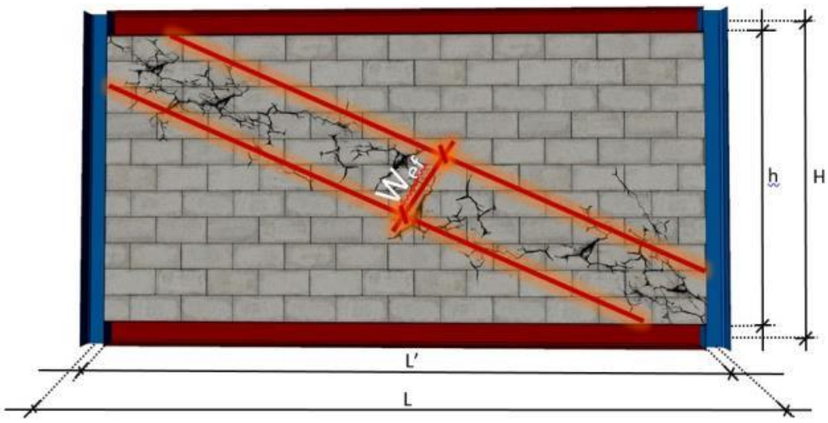


Fig. 7. Equivalent diagonal strut model.

Here, d: diagonal length, t: infill wall thickness, W_{ef}: effective wall thickness, E_m: infill wall elasticity module, E_s: frame elasticity module, H: story height, L: frame opening, L': wall opening, θ: horizontal angle of equivalent diagonal strut, I_c: column's moment of inertia. The numerical values of the diagonal properties of the infill wall were presented in Table 2.

In the examination, the horizontal earthquake force in x-direction has been taken into account whereas the effect of the walls in y-direction has been assessed only as weight. Four different frames have been modeled in ETABS software, non-linear analyses have been carried out under growing earthquake force, and the results have been compared. Evaluation of analysis results four different steel frames comprised of various combinations with infill walls have been modeled in ETABS software and pushover analyses have been performed. The displacements of the models examined which have occurred under the horizontal earthquake force are presented in Figs. 8a-d.

As seen in Figs. 8a-b, Type 2, consisting of infilled steel frames, has more stiffness and increases strength when compared to Type 1 whose frames without infill walls. Fig 8c shows Type 3, in which the basement floor is without infill walls because of various reasons such as commercial purposes and architectural decisions; the floor without infill walls behaves like a soft story under the earthquake force, and the infilled upstairs moves as a whole. In the frame of Type 4 torsion has been observed in which infill walls are distributed asymmetrically (Fig. 8d). The plastic hinges in the frames that have formed under controlled earthquake force have been presented in Fig. 9.

Table 2. Infill wall diagonal properties.

Type	h		λ		W_{ef}	
	Story 1	Story 2	Story 1	Story 2	Story 1	Story 2
	cm	cm	1/cm	1/cm	cm	cm
Type 1	285	270	0.011037298	0.010885136	46.24	46.00
Type 2	285	270	0.011037298	0.010885136	46.24	46.00
Type 3	285	270	0.011037298	0.010885136	46.24	46.00
Type 4	285	270	0.011037298	0.010885136	46.24	46.00

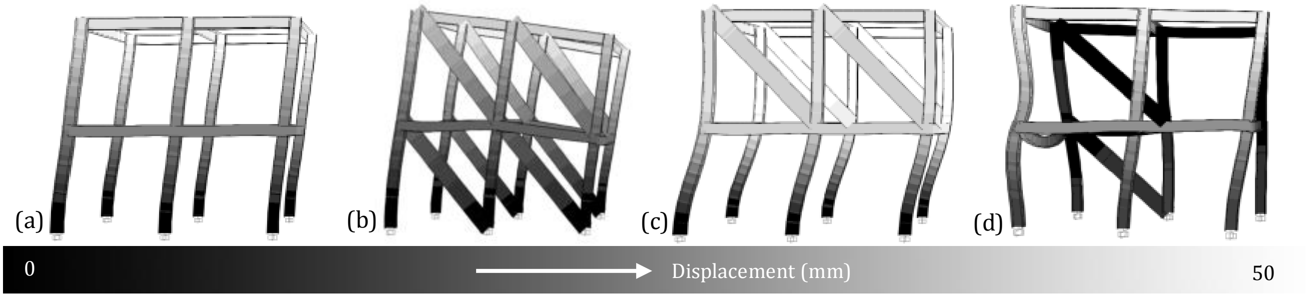


Fig. 8. Displacements due to horizontal load in: (a) Type 1; (b) Type 2; (c) Type 3; (d) Type 4.

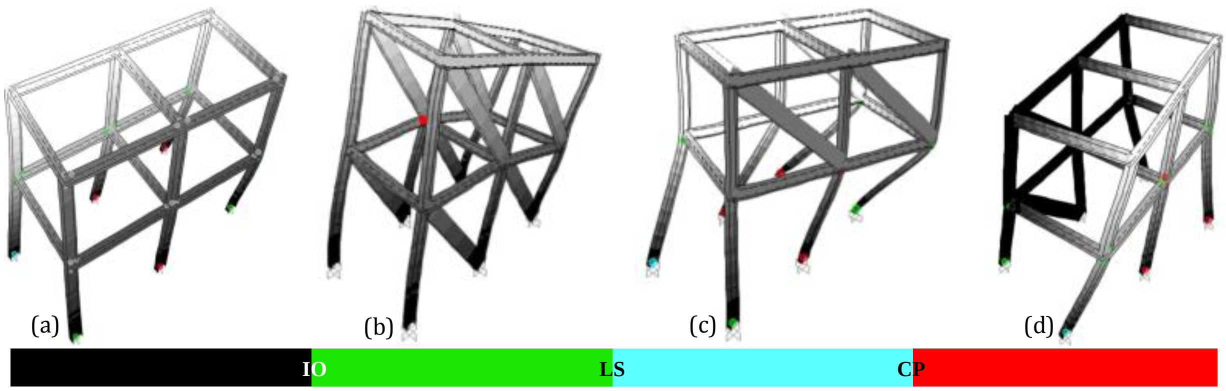


Fig. 9. Plastic hinges in the frames: (a) Frames without infill walls; (b) Frames with infill walls; (c) Effect of soft story; (d) Plastic hinges in asymmetrically distributed infill models.

While the plastic hinges have spread properly in two stories in Type 1, the plastic hinges have formed in the basement floor without walls in Type 3 which is under the effect of soft story (Figs. 9a, c). Since there are not many plastic hinges in Type 2; however, in Type 4, it has been observed that plastic hinges have concentrated in frames which having no infill and failure mechanism has formed (Figs. 9b, d). As a result of the analyses performed for all the cases under the horizontal load, the base shear force and top displacement correlation are shown in Fig. 10a and the maximum story displacements are presented in Fig. 10b.

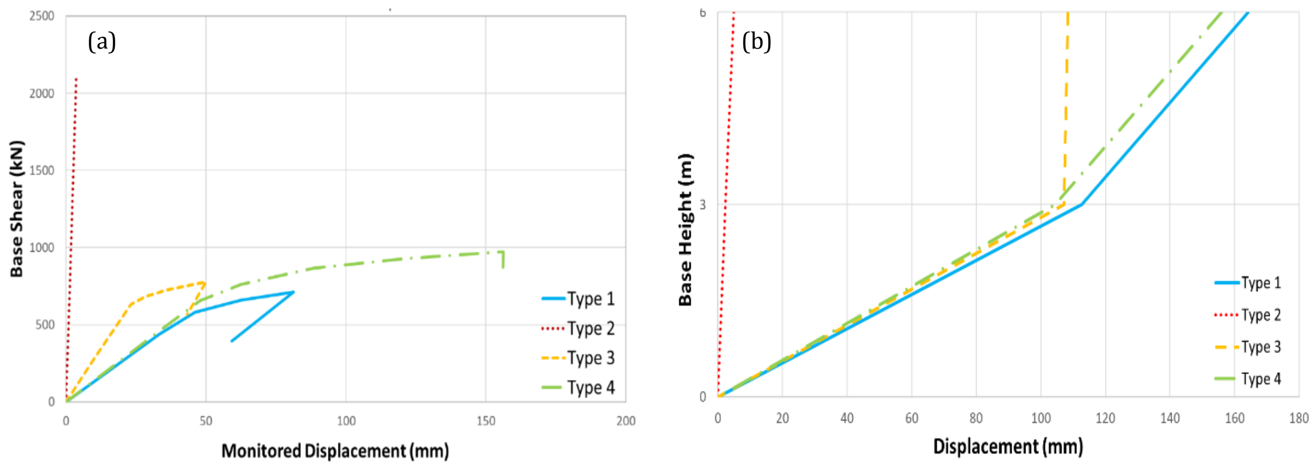


Fig. 10. (a) Base shear force and top displacement; (b) Maximum story displacement.

As is seen in Fig. 10, while the infill walls limit displacement in Type 2 which composed of symmetrical and fully infilled frames, plastic deformations are seen in other cases. In Type 3 with infill walls only in upper story, less displacement was observed in comparison with Type 1 consisting of bare frames due to stiffness of infill walls and weight. As for the Type 4, where there are asymmetrical infill walls in each story, the infill walls have caused torsion in the structure, which has led to even more displacement.

3. Conclusions

Infill walls support the steel frames by increasing the stiffness and strength under earthquake loads. Because of that contribution of infills walls is considered as to be on safe side and positive reserve, the effect of infill walls on structural system is ignored in design. However, infill walls might also lead to some irregularities in the structure, since placing infill walls asymmetrically in vertical and horizontal directions causes certain changes in the stiffness and strength of the structure. That's why, in the draft of 2016 Turkish Earthquake Code, using flexible joint connection between these two elements is stated as an option in order to minimize the effect of brittle infill walls on ductile frames.

In this study, to investigate the effect of infill walls on steel frame structures, four different cases have been determined and their pushover analyses have been performed. As a result of the analyses, it has been determined that infill walls increase strength and limit displacements. Yet, it has also been seen that placing infill walls asymmetrically in vertical and horizontal directions may lead to some irregularities such as soft story and torsion. Steel frames that are structurally far more ductile than infill walls cause deformations under horizontal load, whereas infill walls limit this situation. However, when infill walls and steel frames which have different deformation properties come together, cracks might occur in joints unless necessary precautions are taken.

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