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Effect of Infilled Walls on The Performance of Steel Frame Structures

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Abstract: Today, the subject of a building's resistance to lateral loads is one of the most important concerns of structural engineers. The partitions and infilled walls are non-structural elements that are important due to their effects on the lateral resistance of the building frame. Recently, it has been observed that great damage is occurring to infilled walls, partitions, and buildings in an earthquake-prone area. Infilled walls are effective at increasing the hardness and resistance of building frames, which changes the seismic properties of structures. Therefore, the study of interactions between the structural frame and the infilled walls is essential for a better understanding of structural behaviors. In this paper, the effect of infilled walls is investigated on the behaviour of steel frames using ABAQUS software. Modeling is carried out for different types of infilled materials, including brick and panel, as well as different thicknesses of the infills. It was observed that with an increase in the thickness of infills from 7 to 20 cm, the final capacity and energy absorption increased by 78%. Also, the panel-infilled frames have 18% more capacity and 3.8% more energy absorption than the brick-infilled frame in the same full state. As a result, panel-infilled frames outperform brick infilled frames in terms of performance.

Keywords: Steel structures, infilled frames, shear capacity, energy absorption, finite element

1. Introduction

Civil structures are exposed to damage due to several factors, such as natural hazards and operating loads, which can result in failures or negatively affect the performance of the structures. Therefore, structural damage identification is very important to avoid disastrous failures, minimise the impact of damage, and improve both the safety and functionality of structural systems [1]–[4]. The infilled walls, as non-structural elements, are very significant due to their impacts on the lateral resistance of the frame structures. Structural frames constructed with reinforced concrete (RC) or steel are regularly infilled with walls and panels. Habitually, the existence of these infilled panels is not considered in the process of design. The most important reason is the complex structure of these panels. Also, the

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behaviour of these panels is not fully understood yet. Consequently, the panel and the infilled panel and frame of the structure are designed individually, disregarding their reciprocal effects. A significant issue that is unknown to a designer is that frames and infilled panels complement each other, especially when encountering lateral loads. Therefore, there is still a lack of understanding of the interaction behaviour of structural steel frames infilled with masonry panels, and more research is required. Suffice to say, in recent years, several attempts have been made to understand the behaviour of such systems [5]-[10]. Feiliang et al. [11] found that the infilled part can significantly increase the load-carrying capacity at the flexural stage when compared with the simple frame. There are several problems in determining the combined behaviour of frames and walls. Today, with the development of technology, significant advances have been made in computational software that can be used to study such complicated structural problems. These technologies became increasingly popular through full-scale experiments.

Due to the uncertainties over the accuracy of the numerical models, previous experimental tests can be applied for the purpose of validation. According to Ozkaynak et al. [12], infilled walls increase the stiffness of the structural frame by performing as a compressed diagonal ‘strut-model’ area. Based on this study, ignoring the infill effects on the design of structures, the capacity of the frames is underestimated under lateral loads, since infills increase the strength and stiffness dramatically. The resulting new stiffness in the frames, changes the seismic demands due to the major drop in the natural period of the structural system. Several researchers have also used artificial intelligence techniques to investigate the effect of infilled walls on structural performance [13]-[20].

In recent decades, significant research has been conducted to investigate the effects of infills on structural behaviour [21]-[23]. Based on the experimental and analytical study, Faraji et al. [24] found that the codes’ formulas are conservative and underestimate the real ultimate strength of masonry-infilled steel frames. The main reasons for neglecting the infill wall effects are lacking simplified calculations and inadequate information on the composite behaviour of the frame and the infills. In addition, another reason for disregarding the infill wall effects is the lack of precise experimental and numerical results to prove a reliable design procedure for infill structural systems [25]. As shown in Fig. 1, an infill performs as a diagonal strut model linking the two loaded corners under lateral loads. This mechanism is appropriate in the situation of infills without openings such as doors and windows, which interfere with the distribution of stresses. Furthermore, other investigators [26]-[27] studied the importance of the opening size in infilled frames. Consequently, there is not enough research on the location of the opening in infilled frames. Practically, infill walls affect the lateral displacements of the frame structure. Usually, the separation of the frame and infill walls happens along one diagonal, and a compression strut forms along the other.

As shown in Fig. 1, the mechanism of the load transfer in the structural system has changed from frame action to truss action. Therefore, more axial force applies to the columns while the bending moments and shear forces are reduced. According to these studies [26]-[27], when infill walls are non-uniformly placed in the plan of the building, there is a large concentration of ductility demand in a few members of the structure. For instance, the plan-torsion effect causes excessive ductility demands on frame columns and significantly alters the collapse mechanism, as do the soft-story effect and the short-column effect. In the executive process, the infilled walls are sometimes structurally separated from the frame. The separation may not be adequate to prevent the frame from coming into contact with the infill walls after some lateral displacement; the compression struts may be formed, and the stiffness of the building may increase.

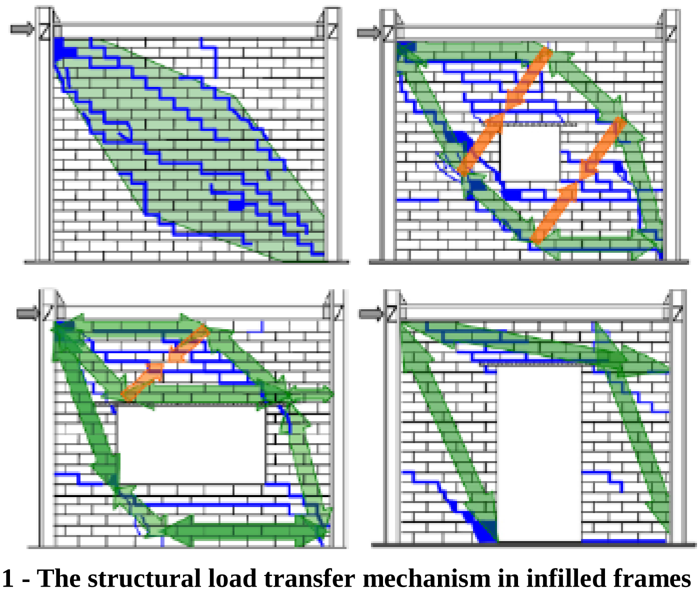


Fig. 1 - The structural load transfer mechanism in infilled frames [27]

Infilled walls have large lateral stiffness and therefore attract a major share of the lateral forces acting on the frame. If the infilled walls are strong enough, the strength they contribute may be comparable to or greater than the strength of the owning plain frame. As a result, the failure of a building is determined by the strength of the frame and infilled walls. In this subject, ductility depends on the infill properties and relative strengths of the frame and infills. Thus, in this study, different infill materials and thicknesses are considered to investigate and compare the system's ductility and energy absorption.

2. Material and Methods

In this study, a 2-dimensional (2-D) 3-floor steel frame has been designed. columns and beams are of plate girder sections of steel-ST37 with a density of 7850 kg/m^3. The height of the floors in all models is 3.2 meters, which is the typical height of floors in residential buildings. A schematic representation of the frame used in the paper is presented in Fig. 2.

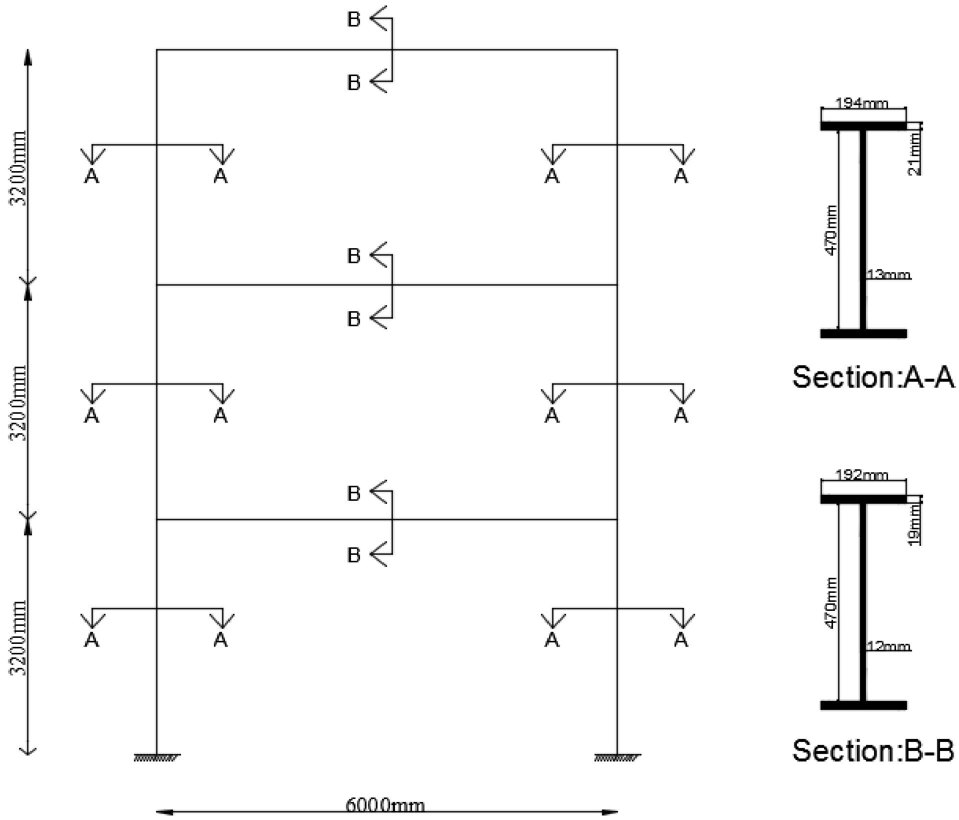


Fig. 2 - A schematic of the designed frame

The material specifications for the steel used in this study are listed in Table 1. Meanwhile, the specifications of materials used in the model are listed in Table 2.

Table 1 - Material specifications for the steel

Characteristic	Parameter	Value
Modulus of elasticity	E	200 GPa
Poisson's ratio	υ	0.3
Special weight	γ	7850 kg/m^3

Table 2 - Infill material specifications

Material	Modulus of elasticity (N/mm^2)	Poisson's ratio	Dimension (mm)
Cement block	20390	0.16	403×206×143
Steel bar	210000	0.3	D = 9mm
Concrete	20000	0.2	-

2.1 Modeling Verification

The modeling of the infilled walls is done using ABAQUS software, and solid elements have been applied to model the frame. In order to model the frame, its components must be constructed as a whole model and then assembled as the final sample under test. A hollow cement block with dimensions of 406×203×143mm is modelled as a component. Materials specifications such as modulus of elasticity, Poisson's coefficient, and compressive strength are entered into the software, as shown in Table 3. Mortar elements are discarded, and their mechanical properties are assigned as contact constraints to all levels of the bricks, and finally, a 2-D frame is modelled as Fig. 3.

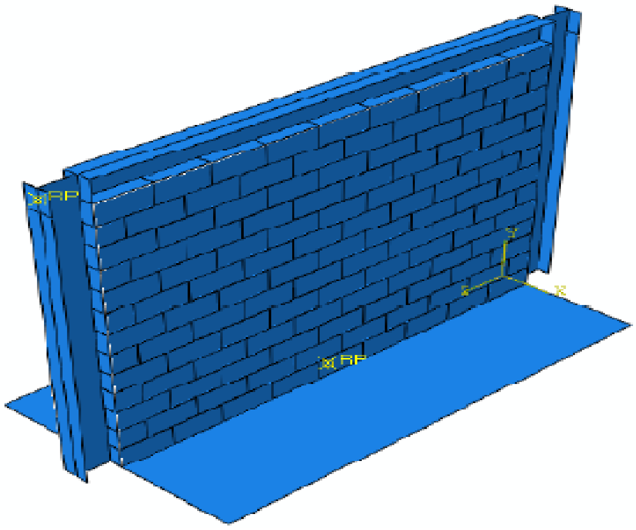


Fig. 3 - Frame modelled using ABAQUS software

In order to ensure the accuracy of numerical modeling, a verified model of the steel frame is selected as the reference, which has been tested experimentally by Tasnimi & Mohebkhah [27]. According to the reference study, reinforcing and modelling of infills are done as shown in Fig. 4.

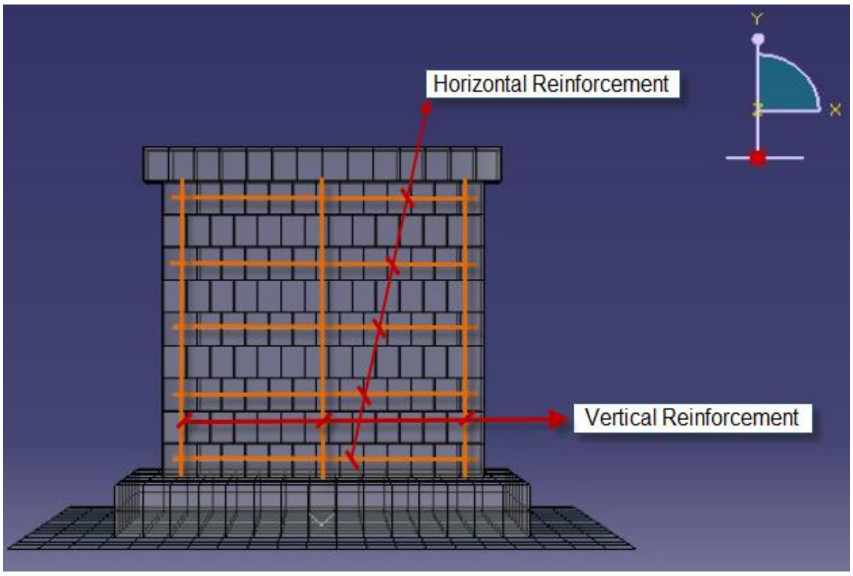


Fig. 4 - Reinforcing and modeling of infilled frames

To apply lateral forces, loading is started from the upper corner of the wall, as shown in Fig. 5. Loading is maintained until the crack phase begins. The loading of the infill frames is considered to be dynamically explicit. Behavioral models used for numerical modelling of laboratory samples in ABAQUS software include the adhesive element, the contact element, and concrete damage plastic (CDP).

The behaviour of infills is properly modelled using the CDP model for 3-D brick elements and the tensile behaviour model for adhesive elements, as shown in Table 3. The applied force to the corner of the infill wall started at zero and continued until the wall collapsed, causing many deformations. Based on the FEMA 302 code, the allowable drift is 0.7 percent for a masonry shear wall. In this study, it is assumed that 0.8 percent of infilled wall models will be destroyed. According to Fig. 5, the applied lateral force is considered the weight of the wall force. The displacement counter of the masonry wall after applying force is shown in Fig. 6. The results showed that the maximum drift of the model is 1.55 cm, which corresponds to 0.8% of wall height. The accuracy of the model has been verified with regard to FEMA 302 code provisions.

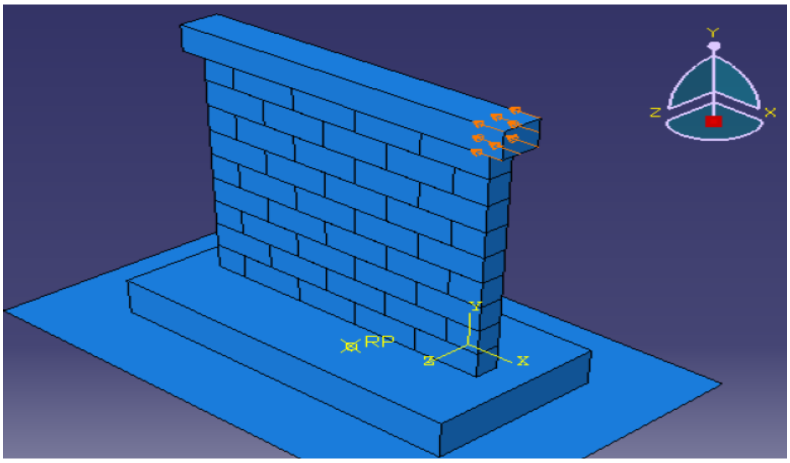


Fig. 5 - Detail of applied lateral loads to the infilled frame

Table 3 - Specifications of materials and elements used in modelling

Cohesive element property	
Elastic property	$Knn = 20e9$, $Kss = 8e9$, $Ktt = 8e9$
Plastic property	$Fn = 0.058$, $fs = 0.14$, $ft = 0.14$ N/mm^2
Contact element property	
Contact friction property	$\tan \varphi = 0.6$
Reinforcement bar property	
Elastic property	$E = 2.3e11$, $\upsilon = 0.3$
Plastic property	$Fy = 420$ MPa, $\varepsilon p = 0$

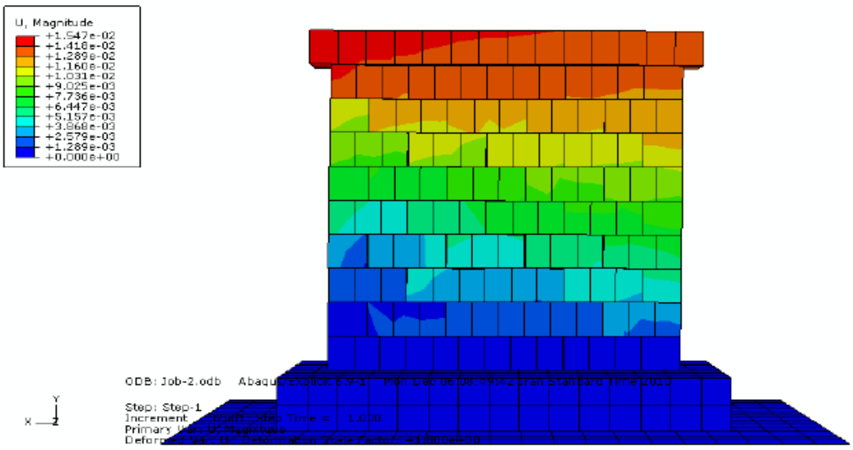


Fig. 6 - Displacement counter caused by applied lateral load

2.2 Analysis Method

The static pushover analysis method is a simplified method for nonlinear seismic response analysis. In this research, one of the simulating lateral inertia forces is placed on the analysing model and enlarged step by step until the structure reaches a target displacement, at which point the seismic behaviour of the structure is evaluated. The hypotheses of static pushover analysis are:

- The seismic response of a structure is related to the equivalent single-degree-of-freedom system. This implies that the seismic response of the structure is only controlled by the first vibration mode.
- Deformation along the structure is expressed by a shape vector. Regardless of the magnitude of structural deformation, the shape vector remains invariant during the seismic deformation process.
- Because floor stiffness in itself is infinite, the stiffness of a plane cannot be considered.

The principles of the static pushover analysis method are:

- Structure is simplified as an equivalent single-degree-of-freedom system. The target displacement is calculated using the maximum inelastic displacement on the effect of fortification level seismic.
- A two-dimensional or three-dimensional model is built for structural analysis.
- Seismic action is simplified as an inverted triangular distribution, uniform distribution, or curve distribution, and then used to calculate the structure's model.
- Performing nonlinear static analysis with load increments until the structural peak displacement equals the target displacement.
- Determine the plastic hinge and continuously modify the total stiffness matrices during the napping process.
- The bearing capacity and deformation of the structure will be applied to evaluate the structure for seismic behavior.

The results of the analysis have been compared with the experimental resultsl. Considering the shape shown in Fig. 7, it is seen that there is a good agreement between the initial strength and the initial hardness of the numerical model and the experimental results.

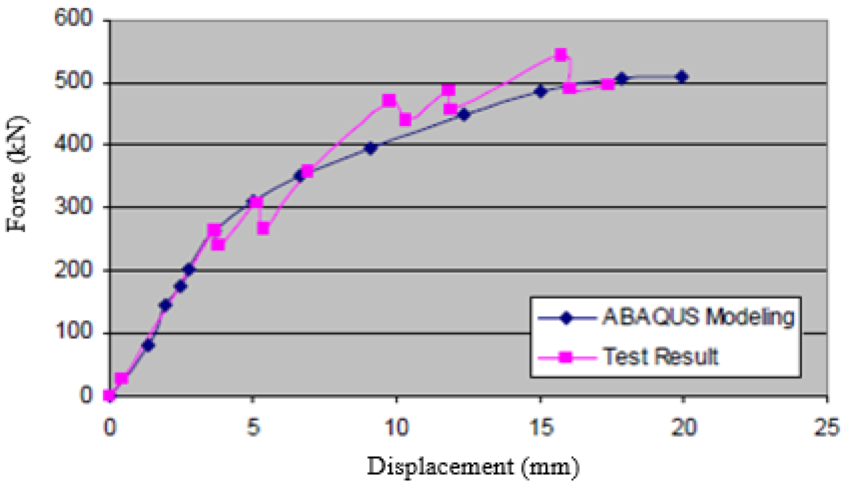


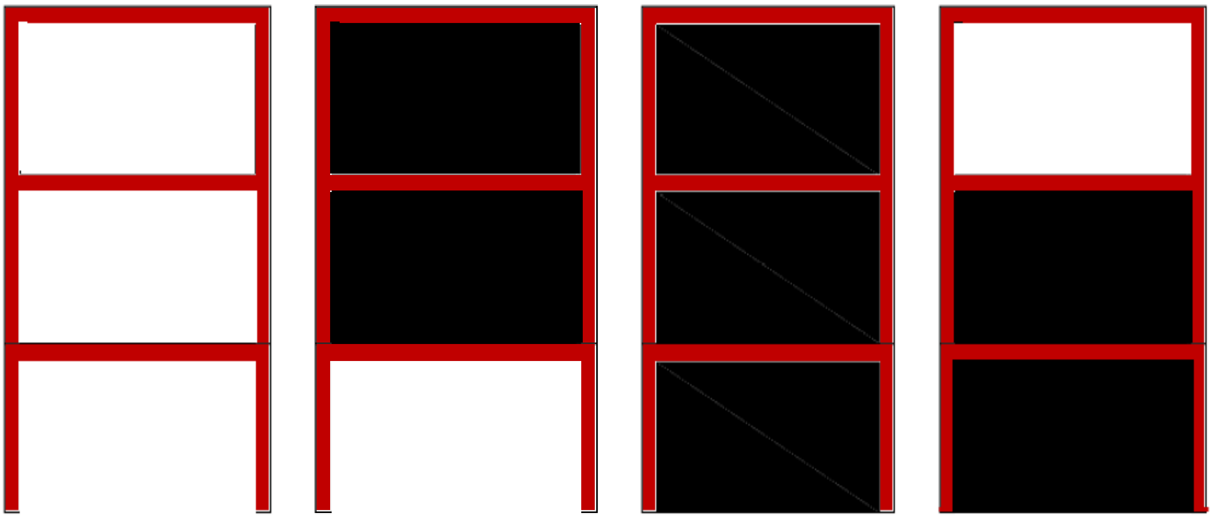
Fig. 7 - Comparison of basic shear force-displacement diagrams for experimental and numerical results

Fig. 7 shows that the final load for the tested model is 534 kN, while it is 510 kN for the model made in ABAQUS software. So, the difference in results is about 4.7%, which is within acceptable limits. In this study, bending steel frames are provided with two types of materials and four common systems: (i) use of brick infills, (ii) use of panel infills with four different layouts, (iii) a non-infilled frame, or "Empty Mode", (iv) all floors except the first have an infilled frame, or are "semi-finished", (v) in "Full Mode " all floors have an infilled frame, and (vi) all floors except the top have an infilled frame.

Regarding the shape of the infilling arrangement of the frames and their type of materials, a total of seven models are introduced:

- (F-1): Non-infilled frames
- (F-2): All floors except the first have brick infilled frames.
- (F-3): All floors have brick-infilled frames.
- (F-4): All floors except the top are brick infilled.
- (F-5): All floors except the first have panel infill.
- (F-6): Frame with panel infills in all floors
- (F-7): All floors except the top floor have panel infill.

Based on the above category and regardless of infill material, the frame systems under study are shown in Fig. 8. Also, in order to study the effect of infill thickness on the behaviour of steel frames, three different panel thicknesses of 7, 10, and 20 cm have been considered and the frame is modelled at 6.0 m long and 3.2 m high.



(a) F-1 (b) F-2, F-5 (c) F-3, F-6 (d): F-4, F-7

Fig. 8 - Infilled frame systems

3. Results and Discussion

3.1 Model Variations

One of the main indices in structural engineering is ductility. The ductility index is used as the basis to evaluate the material behaviour that represents the ability of a member or a system to undergo a large deformation while maintaining its load-resisting capacity [28]. Fig. 9 and Fig. 10 show the shear force-displacement diagrams of brick and panel infilled frames separately.

As shown in Fig. 9 and Fig. 10, the lateral bearing capacity (shear force) increased with the increase in the number of frame openings filled with brick or panel frames. In full-filled frames, it increased dramatically in comparison with other frames. Fig. 11 shows the impact of material types on the final capacity of frames.

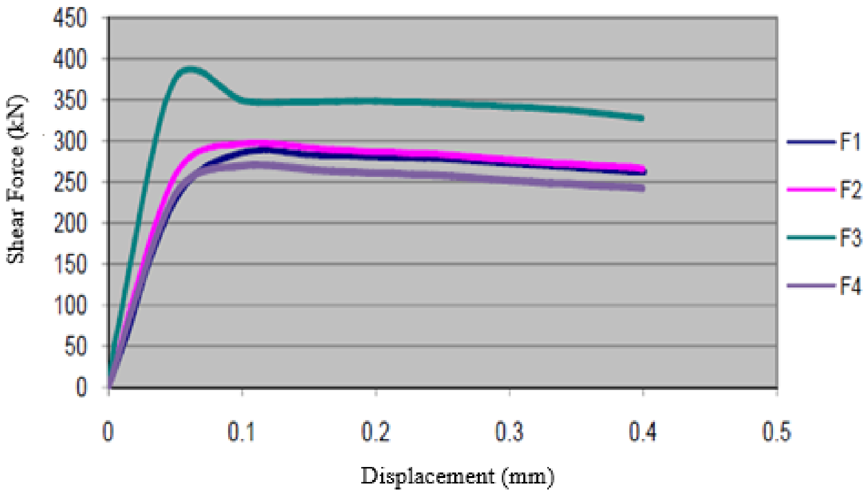


Fig. 9 - Shear force-displacement graphs for brick infilled frame models

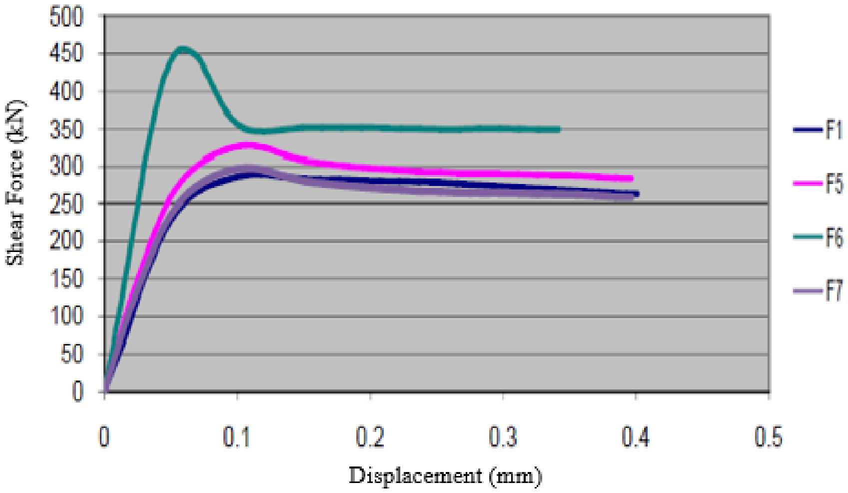


Fig. 10 - Shear force-displacement graphs for panel infilled frame models

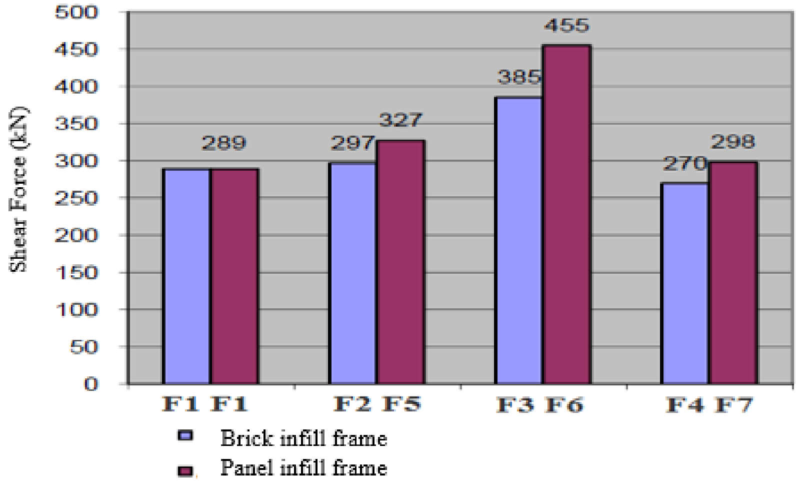


Fig. 11 - Shear capacity comparison in brick and panel infilled frames

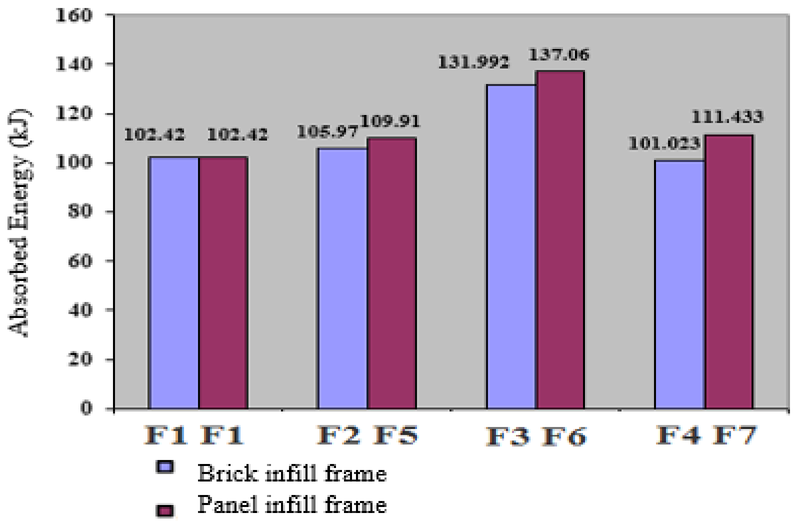


Fig. 12 - Energy absorbed by brick infill and panel infill frames

From Fig.11, it is observed that the panel frames have 18% more capacity than the brick frame in the same case of infilled types. The superiority of panel materials over brick is due to their ability to undergo more deformation without failure. Therefore, panel performance is more effective and ductile than brick-infilled frames.

Increasing structural strength as a single design parameter cannot provide sufficient safety or reduce structural damage alone. One of the main parameters affecting the behaviour of structures is the concept of energy absorption. Therefore, controlling the amount of absorbed energy can control the behaviour of the structure and its damage. The amount of hysteretic energy in a structure is an indicator of the level of damage or its softness. It shows the structural ductility against lateral loads. Fig.12 shows the absorbed energy of the studied frames. It is observed that the panel-infilled frame has 3.8% more energy absorption than the brick-infilled frame in the same full state. Therefore, based on the energy absorption parameter, panel infilled frames' performance is better than brick-infilled frames.

In order to investigate the influence of infill thickness on the behaviour of frames, the modelling of three frames was done at 6 m long and 3.2 m high with three different infill thicknesses of 7, 10, and 20 cm, as shown in Fig. 13.

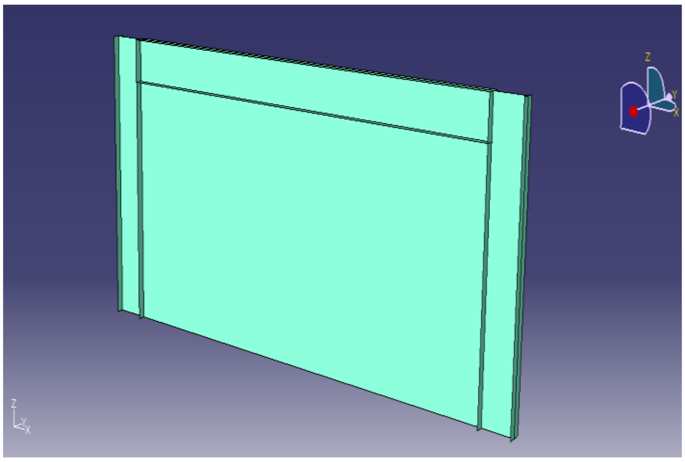


Fig. 13 - The model used to evaluate panel thickness variations

Fig. 14 shows the shear capacity-displacement graphs for all three hicknesses. According to this figure, an increase in the panel thickness for the same displacement results from an increase in the shear capacity of models.

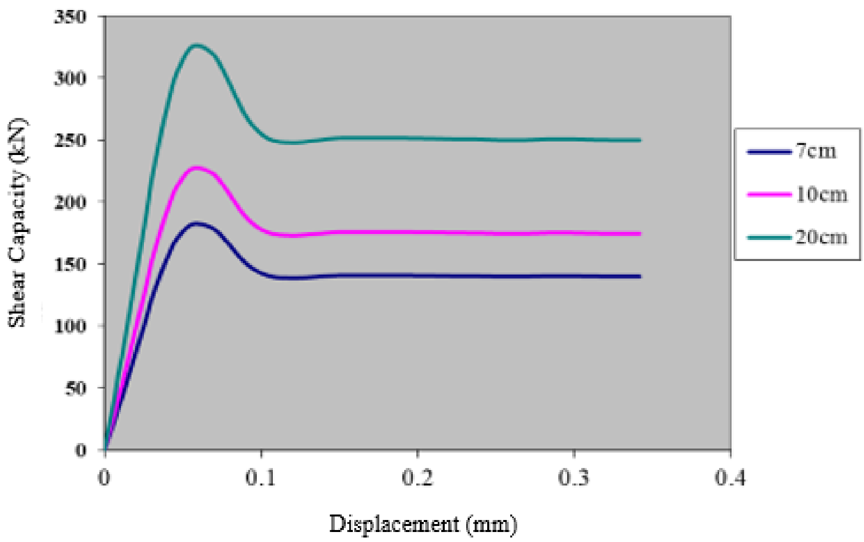


Fig. 14 - Shear capacity-displacement curves for models with different infill panel thicknesses

Fig. 15 shows the final shear capacity and energy absorption of different thicknesses of panel-infilled frames. As can be seen from this figure, increasing the thickness of the panel from 7 cm to 20 cm increases the final capacity from 182 kN to 325 kN, which is a 78% increase in energy absorption.

3.2 Analysis of the Results of the Pushover Cycle

The hysteresis curve is depicted for two modes of modeling, including F3 and F6 models which are shown in Fig. 16 and Fig. 17. According to the results of the models, the maximum force endured is 302.7 kN for the full infilled brick frame (F3), and Fig. 18 shows it as 168.2 kN for F6 as a full infilled panel frame. Thus, it is concluded that by changing the infill materials from the brick to the panel, the endurance force in the final fracture stage has decreased by

44%. Failure occurred in the second cycle of the panel frame model, while failure occurred in the first three cycles of the brick frame model.

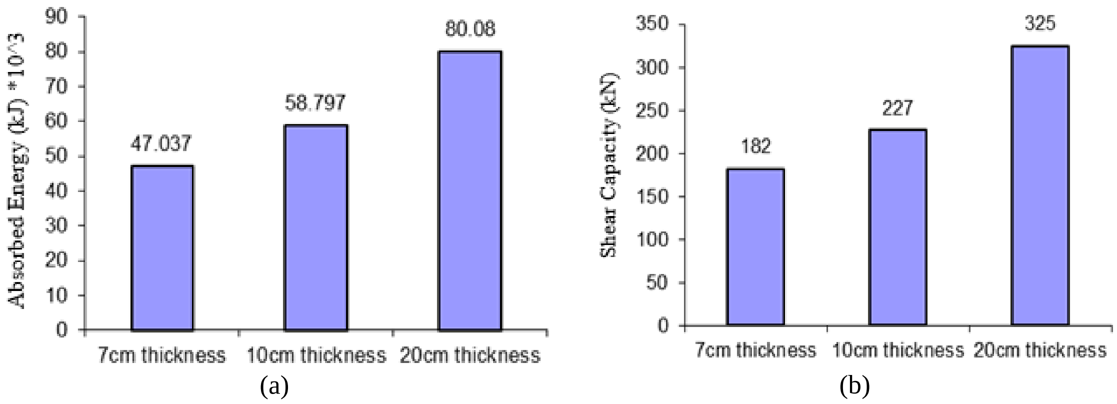


Fig. 15 - (a) Final shear capacity; (b) energy absorption

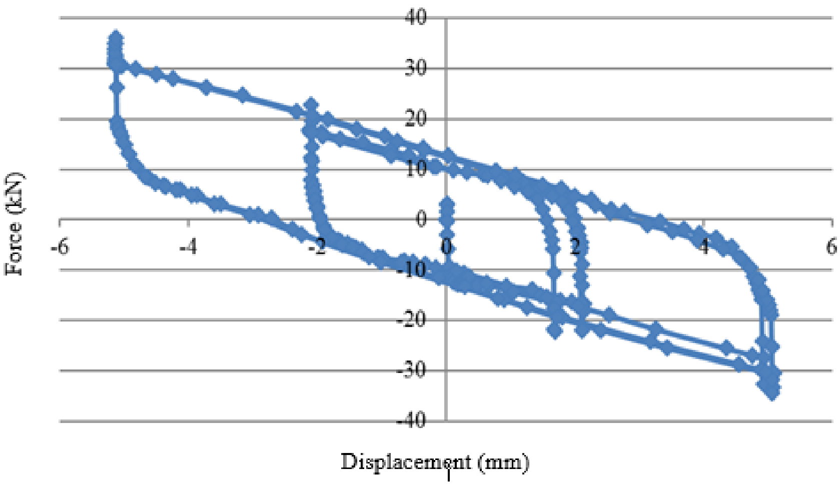


Fig. 16 - Model with full infilled brick frame (F3)

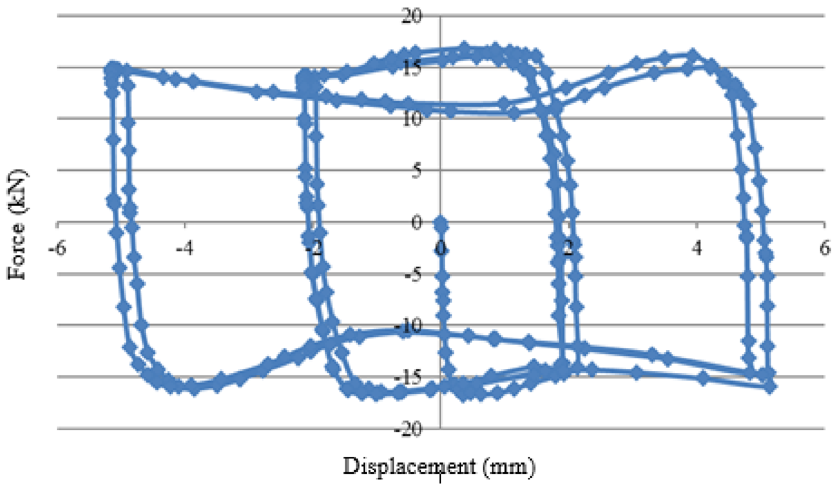


Fig. 17 - Model with full infilled panel frame (F6)

4. Conclusions

Infill walls and partitions are non-structural elements that are important to consider for their effects on the structural behaviour in earthquake-prone areas. These elements are effective in increasing the stiffness of the structures. In this paper, to investigate the effect of infill walls, various infilled frames with different materials and thicknesses are analysed using ABAQUS software. The results confirm that, with an increase in the thickness of the infilled walls from 7 cm to 20 cm, the final capacity increased from 182 kN to 325 kN, which is an improvment of 78% in the shear capacity of the structure. It was observed that shear force capacity increased as the number of frame openings filled with brick or panel frames increased. From the results of this study, it was concluded that by changing the thickness of the infilled from 7 cm to 20 cm, the energy absorption showed a 70% increment. Also in this study, the impact of materials on the final capacity of frames is investigated. In the same case of infilled types, panel frames have 18% more capacity and 3.8% more energy absorption than brick infilled frames.Therefore, panel performance is more effective than brick-infilled frames.

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