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Prediction of the Fundamental Periods for Infilled RC Frame Buildings

Dolgu Duvarlı Betonarme Çerçeveli Binalarda Hakim Periyodun Belirlenmesi

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Abstract

The contribution of infill walls to lateral stiffness and their effect on the natural vibration period of the buildings has been expressed in many studies. An infill wall's effect on the natural vibration period of a building is taken into account by empirical formulas in almost all earthquake codes. These formulations are based on the structures' height and the infill walls are taken into account by a coefficient. However, such parameters like wall thickness, modulus of elasticity of the walls and opening ratio in infill walls are not considered. In this study the effects of the thickness, modulus of elasticity and opening ratio of an infill wall on the natural vibration period are analyzed and the results have been compared with empirical formulas obtained from other studies in the literature.

Keywords: Infill walls, Infill wall modulus of elasticity, Infill wall opening ratio, Infill wall thickness, Structure vibration period

Öz

Günümüze kadar yapılan çalışmalarda, dolgu duvarların yanal rijitliğe olan katkısı ve bina periyoduna etkisi belirlenmiş, hemen hemen bütün deprem yönetmeliklerinde dolgu duvarların bina periyod değerlerine etkisi ampirik formüllerde bir katsayı olarak dikkate alınmıştır. Ancak dolgu duvarların elastisite modülü, kalınlığı ve dolgu duvarda yer alan boşlukların etkisi gibi parametreler ampirik formüllerde yer almamıştır. Bu çalışmada, dolgu duvarların elastisite modülünün, kalınlığının ve boşluk oranlarının periyoda etkisi nümerik modeller üzerinde analiz edilmiş ve diğer çalışmalarda elde edilen ampirik formüllerle karşılaştırılmıştır. Elde edilen sonuçlar mevcut binalar üzerinde kontrol edilmiştir.

Anahtar Kelimeler: Dolgu duvar, Dolgu duvar elastisite modülü, Dolgu duvar boşluk oranı, Dolgu duvar kalınlığı, Yapı titreşim periyodu

1. Introduction

In Turkey, the seismic effects on the buildings are very important during the design and construction due to its location which is one of the most important seismic belts on the earth. In the process of designing a reinforced concrete structure in Turkey, infill walls are not considered as structural elements in numerical modelling and only their weight is taken into account as a static load (Furtado et al. 2015). Because of the complexity of creating models in which contribution of infill walls and the variability of the mechanical properties of the materials are taken into account, the effects of the infill walls have been omitted during analytical calculations (Asteris et.al 2015). However, in some of the seismic codes in various countries the effect of infill walls on a building's vibration period is somewhat taken into account by empirical formulations but in these empirical formulations, the infill wall thickness, modulus of elasticity of infill walls and infill wall opening ratios are not usually taken into account. Infill walls may be beneficial for increasing the strength of structures by increasing lateral stiffness, infill walls mostly increase the lateral load caused by seismic forces. It is not accurate to say that it is safe by taking into account the infill wall's weight while not calculating the increase in lateral stiffness. A reinforced concrete structural system must be safe, which means the effect of the infill wall should be taken into account as well. The true behavior of the structure can only be obtained by considering the effects of the infill wall and only then a safe design can be accomplished. Some do not consider infill walls as structural elements but studies have proved that the lateral stiffness of the infill walls can change the structural behavior from a seismic effect.

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Polyakov (1960), was the first to study the behavior of frames with infill walls. Al-Chaar (2002) studied the behavior of infill walls and compared the locking behavior of the frame which has equivalent virtual strut frames and stresses with the frame with an infill wall in which the stresses are transferred at compressive regions within the frame – that is, with the infill wall interface which has a typical distribution across the locking system beyond the homogeneous shear wall.

Equivalent virtual strut frames which is the foundation of estimating lateral stiffness and lateral strength of structures with infill walls have been used based on experiences during the 1960's for small-scale frames with a mortar infill (Stafford-Smith and Carter, 1960).

Fiorato et al. (1970) showed that in addition to the contribution to lateral stiffness, the infill walls make a large contribution to the lateral strength and amount of damped energy as well by using dynamic analysis in multi-story building models.

Based on the result of many studies on bare frame walls and frames with infill walls, Zarnic and Tomazevic (1998) observed that the strength and stiffness of frames with infill walls is greater than that of bare frame walls. For this reason, the effects of the infill wall should be considered in the construction phase as well. However, in cases where the effects of the infill wall are not considered, the infill walls should be separated with a suitable joint in the structural system.

One quarter of the diagonal length of the infill wall is recommended as the well-advised virtual strut frame width and nearly all the stresses are carried by the infill wall before the lateral joint slip (Paulay and Priestley 1992).

Fardis and Panagiotakos (1999), carried out an experiment to show that the stiffness of the infill based on the wall distribution on the plan, has an important effect on the structure's behavior in an earthquake.

Goel and Chopra (2000), proposed some formulations for determining the structure vibration period by assessing the records of many earthquakes which are recorded for reinforced concrete framed buildings, reinforced concrete shear walled buildings and steel framed buildings (Goel and Chopra 1997), (Goel and Chopra 1998). In addition, they had some proposals for predicting seismic displacements.

Al Chaar and Lamb (2002), experimented on determining the seismic weaknesses of old building which are designed considering only vertical loads. The experiments show that the frame with an infill wall has a higher initial stiffness and higher strength than a bare frame. Furthermore, in this study, the span number affects the capacity, collapse mode and shear stress distribution of structures as well.

In the analytical study, which was done by Amanat and Hoque (2005), it was shown that the fundamental vibration period of a structure with bare framed reinforced concrete is higher than the calculated period using formula in seismic code. However, they proposed that vibration periods was obtained when infill walls are taken into account are close to those which are calculated according to code formulae. In their analysis, they observed that the infill wall's distribution in the structure is not important on the structure's vibration period. However, the quantity of infill walls is very important for the structure's vibration period. They did their analysis with buildings with various number of stories, for various story heights, span numbers, span dimensions and infill wall quantities. In these analyses, they used a constant infill wall modulus of elasticity and infill wall thickness.

The majority of the investigations focused on infill walls without door and window openings. However, it was observed that infill walls with door and window openings are less stiff than infill walls without door and window openings (Asteris 2003).

Celep and Gencoglu (2003), studied the behavior of a reinforced concrete framed building with infill walls which had weak column sections and simple geometry, under seismic load. The shear force of an earthquake affects the infill walls and the columns in the direction of the earthquake. The shear force of an earthquake also affects the infill wall area and the connection between the infill wall and the surrounding wall. The beams above and below and the columns which are located on both sides of the wall were also investigated. As a result of the investigation, it was understood that the effect of the infill wall is to increase the lateral stiffness of buildings. While using infill walls, careful attention should be paid to the importance of the quality of mortar and workmanship and high ductility as well as the capacity of the infill walls, including those without openings.

Crowley and Pinho (2004), studied the derivation of a simple empirical yield period-height formula for use in the displacement-based assessment of European buildings. These formulae are available in many design codes and they relate to the height of a building to its fundamental period of vibration.

Budak (2006), showed that infill walls cause an increase in constant structural loads. A building's vibration period is decreased considerably with an increase in stiffness, which is created by infill walls. Infill walls cause first modes to be more effective on earthquake loads. Spectrum values can both increase and decrease depending on the use of the spectrum curve. As a result, it was shown that the earthquake loads of structures can be increased by infill walls.

Gürler et al. (2006), have investigated the fundamental periods of reinforced concrete structures. It has been observed that the fundamental periods of the structures have been affected by the infill walls.

Güler et al. (2008), compared the vibration periods, which were obtained from the numerical model with those from the experimental study and it was observed that the results were considerably close to each other. According to the results, a formula was developed for identifying the effect of infill walls on both the structure period and reinforced concrete framed buildings with infill walls. This formula depends on height.

Asteris et al. (2015), have completed a detailed research on parameters affect the vibration periods of the structures and compared the parameters with calculations by the suggested formations on seismic codes. Based on their study, number of storeys, number of spans, infill wall stiffness, the location of weak story, and soil class have important effects on vibration periods.

Panzera et al. (2016) have investigated the periods of various reinforced concrete and masonry structures and stated that the periods obtained by experimental results are always smaller than the periods calculated by formulations given in the codes.

The effects of infill walls on structures using both numerical and experimental studies are shown. In addition, the empirical formula for the fundamental vibration periods for buildings, which was proposed by the NEHRP 1994, UBC 1997, EC8 2003 and TDY 1998, is taken into account. Like today's earthquake codes, the effects of infill walls are also considered. Empirical formulas used in these codes depend on structure height and infill walls (which are represented with a coefficient). However, there are several studies which associate the effect of infill walls on vibration period with infill wall ratio in the structure.

In this study, the effects of infill wall thickness, modulus of elasticity and opening ratio to vibration period as well as a comparison with the formulae of the proposed codes is investigated.

2. Materials and Method

In this study, a reinforced concrete framed building model with 4 spans in one direction and 5 spans in the other direction which was used on different studies by Koçak and Yıldırım (2011) have been used. The length of the building span in the short direction is 6m and the span length in the long direction is 5m. The height of the building is 3m and the various number of story such as 3, 6, 9 and 11 are taken into account in this study. Column and beam dimensions are designed separately for four different story levels (Figure 1).

Infill walls are modelled with equivalent compression struts which are hinged at both ends and have the exact axial stiffness that is recommended by Ersin (1997) and Güler et al. (2008). These frame elements have axial stiffness that is equivalent to that of infill walls when calculated using the formula below:

$$EA: E \times t \times \alpha \times L_d \times \beta \times \gamma \quad (1)$$

E: Modulus of elasticity of infill wall (MPa), (Table 1)

t: Thickness of infill wall (mm)

L_d: Diagonal length of infill wall (m)

α: Coefficient for definition of equivalent frame element's efficient width compared with equivalent frame element's length

β: Coefficient for taking into account opening ratio in infill walls, (Table 2)

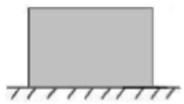
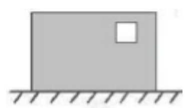
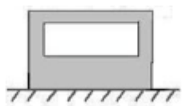
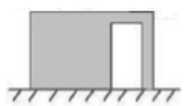
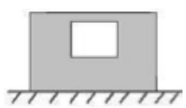
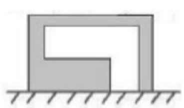
γ: Coefficient for taking into account all the other effects

Modelling infill walls, which are manufactured from low strength bricks which are equivalent to frame elements having axial stiffness, depends on the infill wall modulus of elasticity, thickness and opening ratio of an infill wall as shown in Equation (1). According to the results of experimental studies by Ersin (1997) the recommended values for the modulus of elasticity of infill walls are given in Table 1 and the values for the β coefficient, which is taken into account when calculating the opening ratio in infill walls that are suggested by Koçak, Kalyoncuoğlu, and Zengin (2013), are given in Table 2.

Table 1. The modulus of elasticity of infill walls.

Infill Walls	E_{par} (MPa)	E_{ver} (MPa)	E_{ave} (MPa)
Unplaster	4600	2500	3500
Plaster	7800	4200	6000

Table 2. β Coefficients of infill walls.

Type		β
D1 (Infill Wall)		1
D2 (Infill Wall with Small Window Openings)		0,9
D3 (Infill Wall with Big Window Openings)		0
D4 (Infill Wall with Door Openings)		0,5
D5 (Infill Wall with Windows)		0,2
D6 (Infill Wall with Door/ Windows)		0

Koçak and Yıldırım (2011), studied the equivalent frame elements which are used for modelling infill walls. In the study, the cross-sectional area was 0.1m^2, the average modulus of elasticity for a plastered infill wall was 6000 MPa and the poisson ratio was 0.3. Furthermore, the β parameter was taken into account in representing type D5 openings in all the outer walls and type D4 openings in all the inner walls. In the study, the buildings which has a floor plan like Figure 1, was designed with 3, 6, 9 and 11 stories and was analyzed by taking into account the infill wall opening ratio, modulus of elasticity and thickness for the bare framed condition, with modelling of the infill walls for all the axes and various infill wall ratios. In addition, the vibration period formulation (2) which depends on wall area / [structural element (column area) + wall area] was obtained and this.

Obtained relationship:

$$\Delta T(\%) = 69.1 \times A_k^{1,08} \text{ and } T_d = T_c \times \left(1 - \frac{\Delta T}{100}\right) \qquad (2)$$

In this relationship:

ΔT: The ratio of decrease (%) in the period with infill walls compared with the period without infill walls

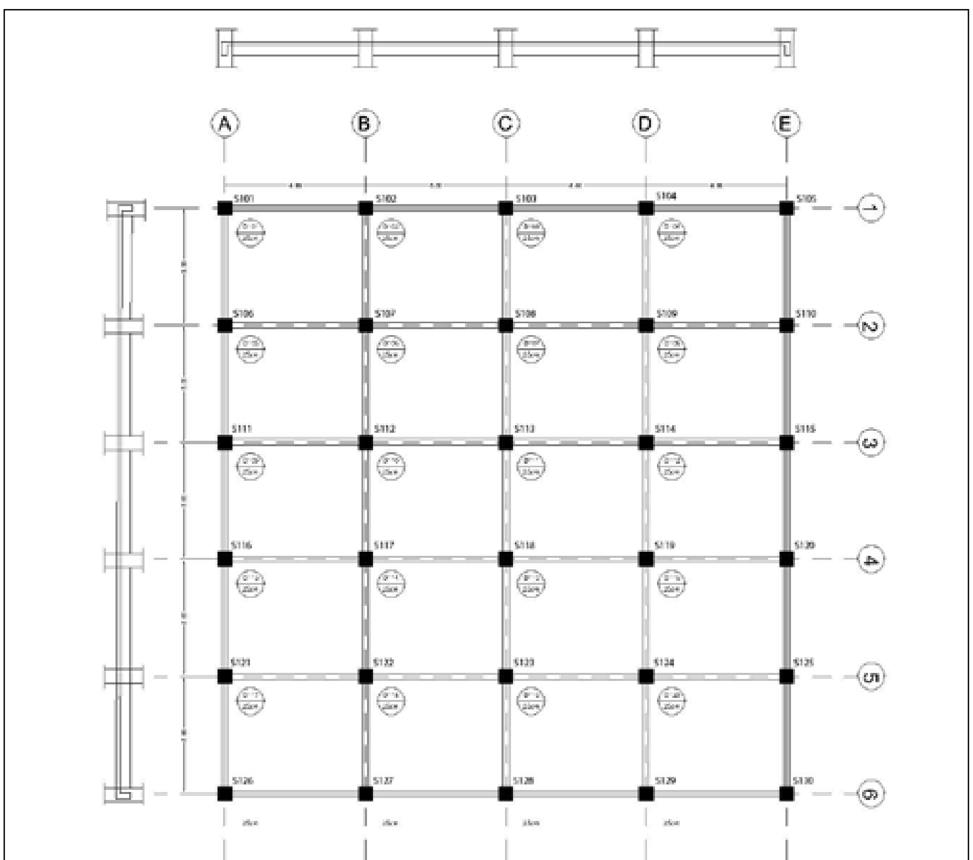


Figure 1. Floor plan.

A_k: The wall area / [structural element (column area) + wall area]

The period with infill walls can be found using $T_d = T_c$ x $(1-\Delta T(\%))$ formula by using the period without infill walls

T_d: The period of buildings with infill walls

T_c: The period of bare framed buildings without infill walls

Note that this relationship is obtained for an average modulus of elasticity for plastered infill walls (Table 1), for a constant infill wall thickness and for normal window and door openings (Table 2), which can be seen in an average building. In the study, E: 6000 MPa, thickness for inner walls is 10 cm and for outer walls is 20 cm and the β coefficient for the opening ratios in the infill walls is type D4 and D5 are selected.

The building shown in Figure 1 was first analyzed for the bare framed condition and with modelling infill walls for all axes for different values of the mentioned parameters in 4 different story levels (Figure 2). Next, this analysis was done for various infill wall ratios. These analyses were repeated for different infill wall modulus of elasticity, infill wall thicknesses and infill wall opening ratios. In this study, infill wall modulus of elasticity values were taken into account with variations between 2500-7800 MPa as shown in Table 3. Infill wall thicknesses were taken into account with variations between 100-300 mm and their opening ratios were taken into account by decreases of 40 and 80% and by increases of 40 and 80% as shown in Table 3. The effects of changing these parameters are investigated in graphs.

Table 3. Parameters used in the study.

E (MPa)	2500 – 3500 – 4200 – 4600 – 6000 – 7800
t (mm)	100 – 150 – 200 – 250 – 300
β (D4-D5)	%40 – %80 (Decrease in opening size), %40 – %80 (Increase in opening size)

3. Analysis Results

The buildings have been analyzed by SAP2000 considering diferent values for wall thicknesses, modulus of elasticity and openings. The effect of these parameters on the fundamental periods for infilled RC frame structures have been investigated.

3.1. Effect of Infill Wall Thickness

The infill wall thickness that have been used in the study completed by Koçak and Yıldırım (2011) was 100mm and the formulation of the results are. The appropriate equations which have been obtained by using regression analysis to the results for different infill wall thicknesses have been shown in Figure 3.

As seen in Figure 3 the decrease in period for different wall thicknesses is between 9%-27% compared to 10cm wall thickness. The effect of the infill wall thickness on the free vibration period of the structure has been given in Table 4 for different story levels.

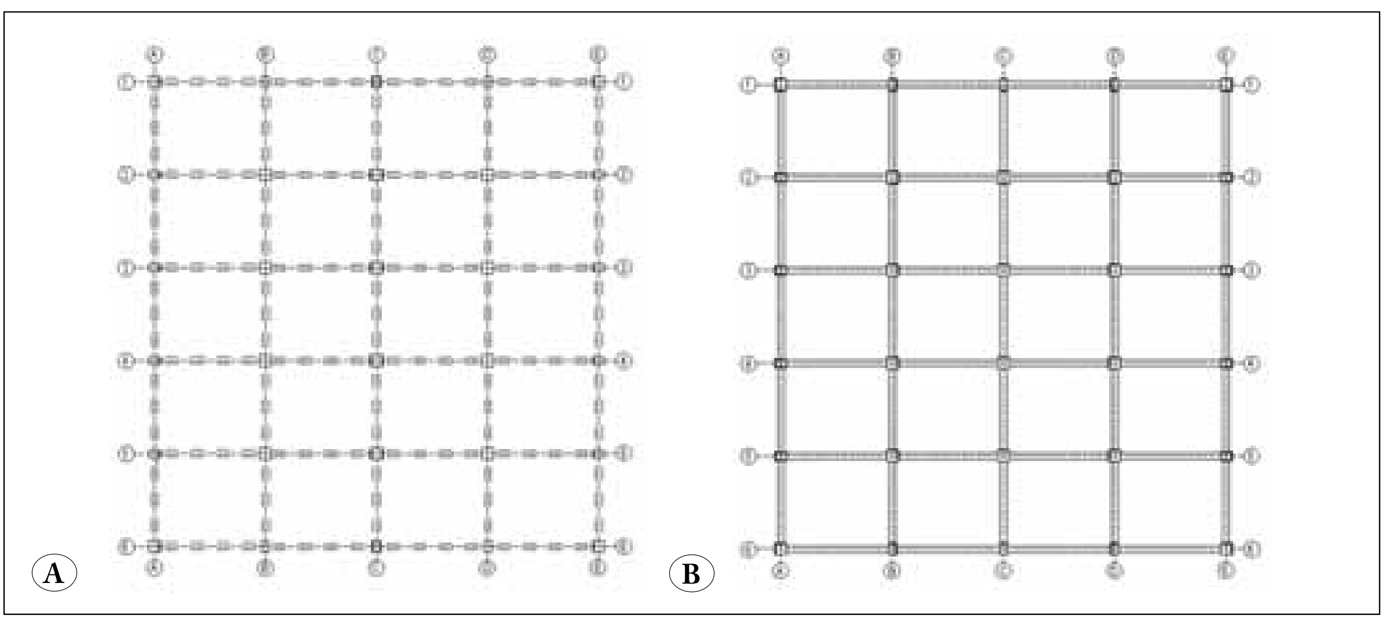


Figure 2. Infill wall configuration. **A)** Frame (without infill wall), **B)** Whole wall (with infill wall).

3.2. Effect of Modulus of Elasticity

For the purpose of investigating the variation of infill modulus of elasticity for the above building model, the infill wall modulus of elasticity was taken to be between 2500-7800 MPa and the results obtained are shown in the relationship Figure 4 shows the analysis of the results for different modulus of elasticity values. A regression analysis was applied to every modulus of elasticity and the results were analyzed to obtain the most suitable curve in relation to format in order to compare the effect of different infill wall modulus of elasticity on the period. All the equations are shown in the corresponding graph. There are different coefficients for different modulus of elasticity and the k_E values differ from 41 to 78.53.

By benefiting from the proportion between the equations, the coefficient "a" can be improved in order to reflect the effect of different modulus of elasticity as shown in Figure 5. "a" can be calculated for any desired modulus of elasticity with formula. As a result, $\Delta T(\%){:}\, 69{,}1 \times A_k^{1{,}08}$ is divided by "a" and the equation becomes $\Delta T(\%){:}\, \dfrac{69.1 \times A_k^{1{,}08}}{a}$.

Table 4. The effect of the infill wall thickness to free vibration period.

Storey Number	Infill Wall Thickness									
	Td = Tc.(1- k_t.Ak$^{1.08}$/100)									
	k_t = 69.10		k_t = 68.23		k_t = 68.57		k_t = 68.96		k_t = 69.29	
	t = 10 cm		t = 15 cm		t = 20 cm		t = 25 cm		t = 30 cm	
	Tx (s)	Ty (s)	Tx (s)	Ty (s)	Tx (s)	Ty (s)	Tx (s)	Ty (s)	Tx (s)	Ty (s)
3 Storey	0.253	0.248	0.229	0.224	0.212	0.207	0.200	0.194	0.191	0.185
6 Storey	0.445	0.435	0.402	0.391	0.370	0.360	0.348	0.337	0.332	0.321
9 Storey	0.607	0.571	0.546	0.513	0.502	0.472	0.471	0.441	0.448	0.419
11 Storey	0.702	0.682	0.631	0.614	0.580	0.563	0.542	0.526	0.515	0.498
Decrease in Period (%)			9-10		16-17		21-22		24-27	

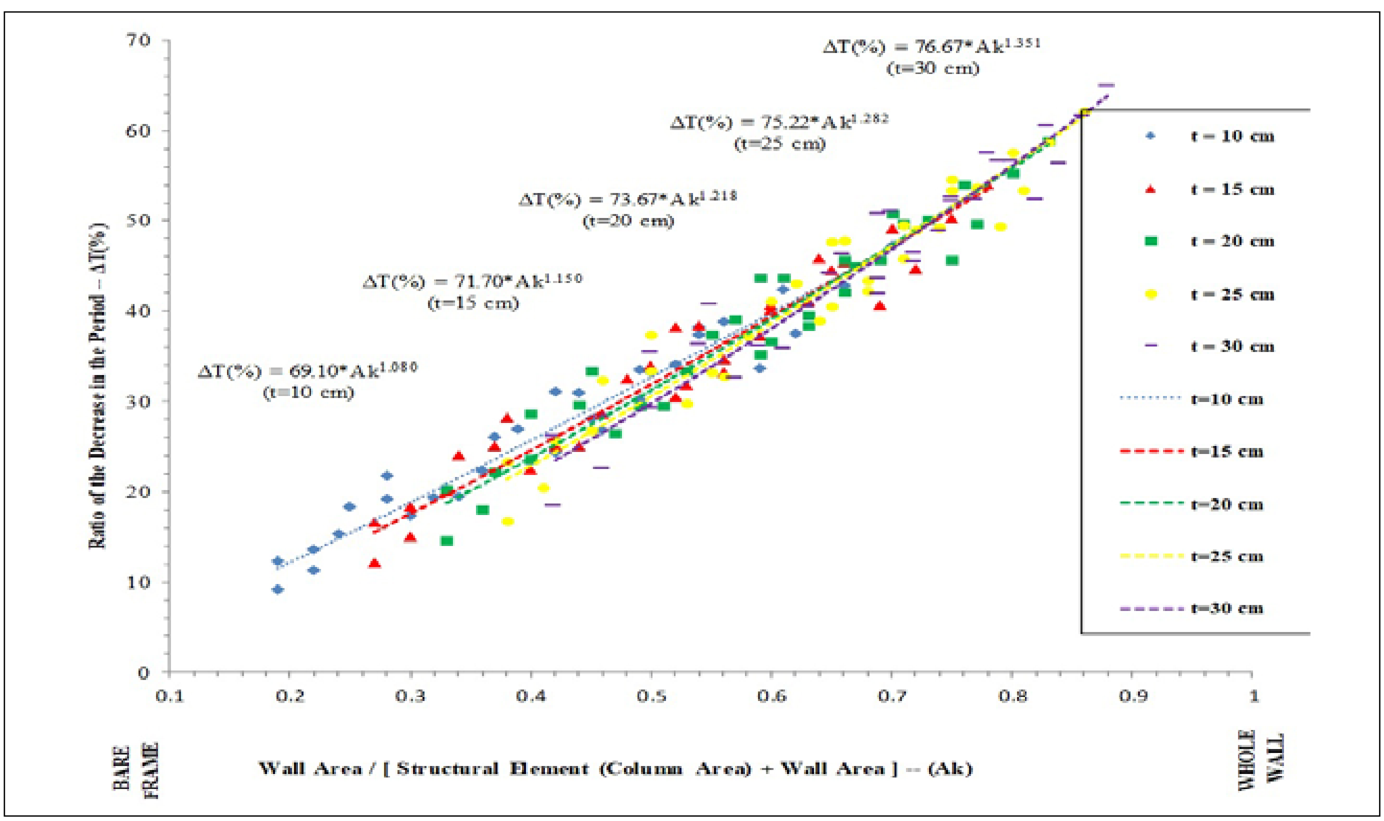


Figure 3. Decrease in period / infill wall area for various infill walls.

a: Coefficient, which reflects the infill wall modulus of elasticity

E: Infill wall modulus of elasticity

Table 5. gives the periods based on using the equation in analytical models. In all models infill walls without openings and infill walls with same openings have been used. The effect of different modulus of elasticity to the vibration

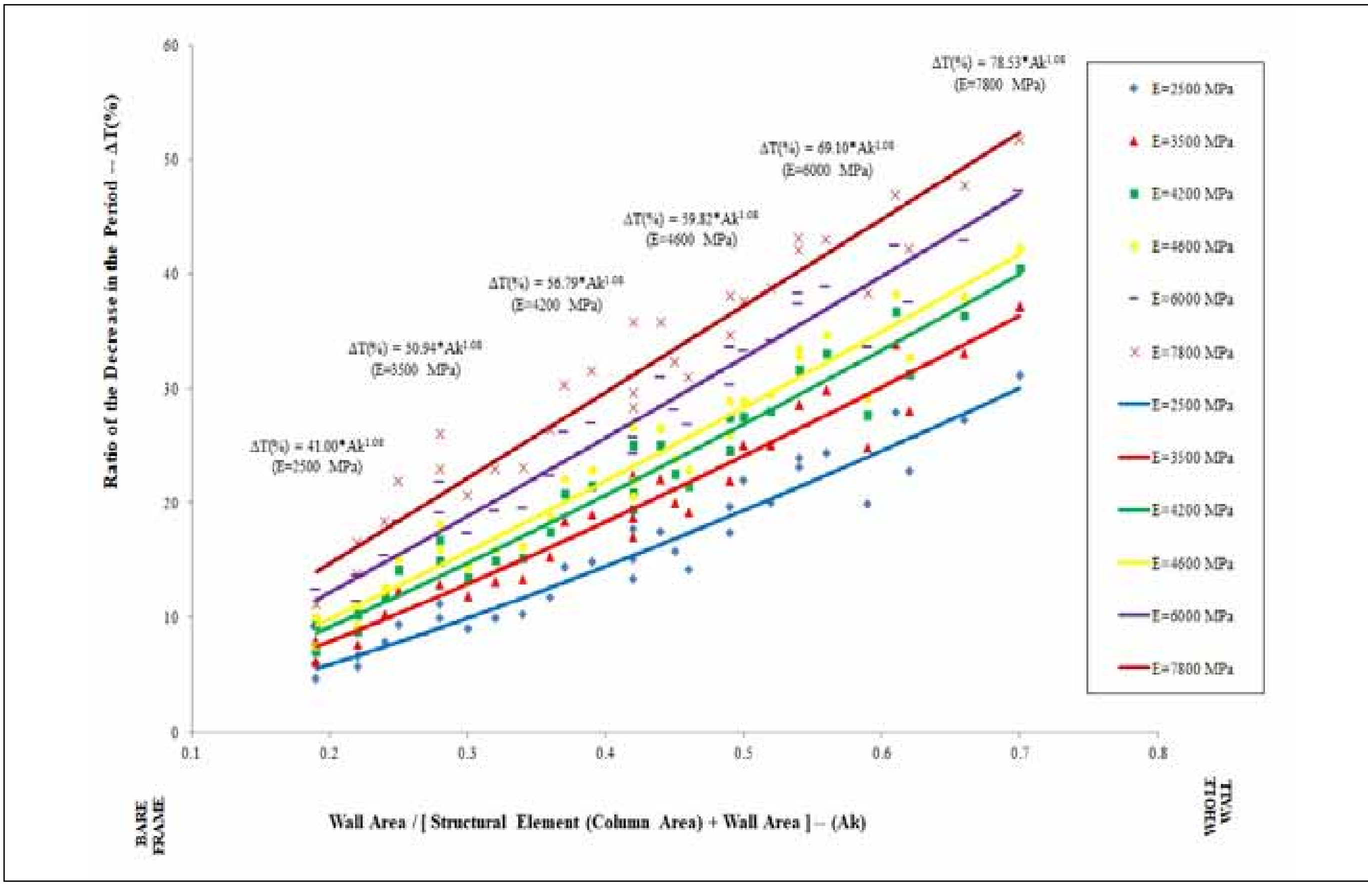


Figure 4. Decrease in period for diffferent elastisity modulus / infill wall area for various infill walls.

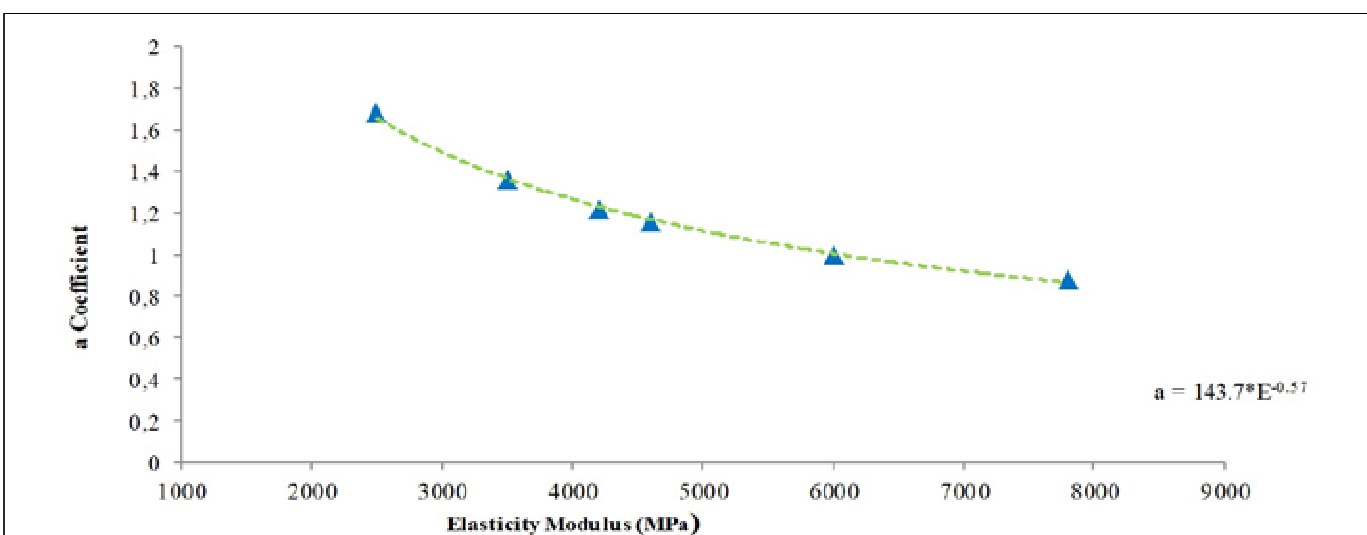


Figure 5. Relationship between a coefficient and modulus of elasticity.

period have been investigated for E=2500 MPa value. The decrease in the period is between 65 and 35%.

3.3. Effect of Infill Wall Opening Ratio

In the obtained relationship (2), D4 and D5 type opening ratios were used in infill walls in building the numerical model. A D4 type opening corresponds to an 80X200 (cm) door-opening while a D5 type opening corresponds to a 140X120 (cm) window opening. In this study, period values were investigated for both increasing and decreasing cases of D4 and D5 type opening ratios. Curves of the ratios showing a decrease in the period are shown in the following figures for varying opening ratios and different infill modulus of elasticity for each case (Figure 6; Figure 7).

In order to reflect the infill wall opening ratio, coefficient "a" can be calculated as a=332.93. $E^{-0.667}$ for 40% decrease in wall opening ratio, a= 1655.5 $E^{-0.852}$ for 80% decrease in wall opening ratio, a=83.815 $E^{-0.509}$ for 40% increase in wall

Table 5. The effect of modulus of elasticity in vibration period.

Number of Storeys	Modulus of elasticity											
	$Td = Tc.(1- k_E.Ak^{1.08}/100)$											
	k_E = 41.00		k_E = 50.94		k_E = 56.79		k_E = 59.82		k_E = 69.10		k_E = 78.53	
	E = 2500 MPa		E = 3500 MPa		E = 4200 MPa		E = 4600 MPa		E = 6000 MPa		E = 7800 MPa	
	Tx (s)	Ty(s)	Tx (s)	Ty(s)	Tx (s)	Ty(s)	Tx (s)	Ty(s)	Tx (s)	Ty(s)	Tx (s)	Ty(s)
3 Storey	0.344	0.329	0.311	0.301	0.292	0.284	0.283	0.275	0.253	0.248	0.222	0.221
6 Storey	0.589	0.560	0.538	0.516	0.508	0.490	0.493	0.476	0.445	0.435	0.397	0.392
9 Storey	0.782	0.719	0.720	0.666	0.683	0.636	0.665	0.620	0.607	0.571	0.548	0.522
11 Storey	0.884	0.840	0.820	0.784	0.782	0.751	0.762	0.734	0.702	0.682	0.641	0.629
Decrease of the Period (%)			**6-9**		**10-15**		**12-18**		**18-27**		**25-35**	

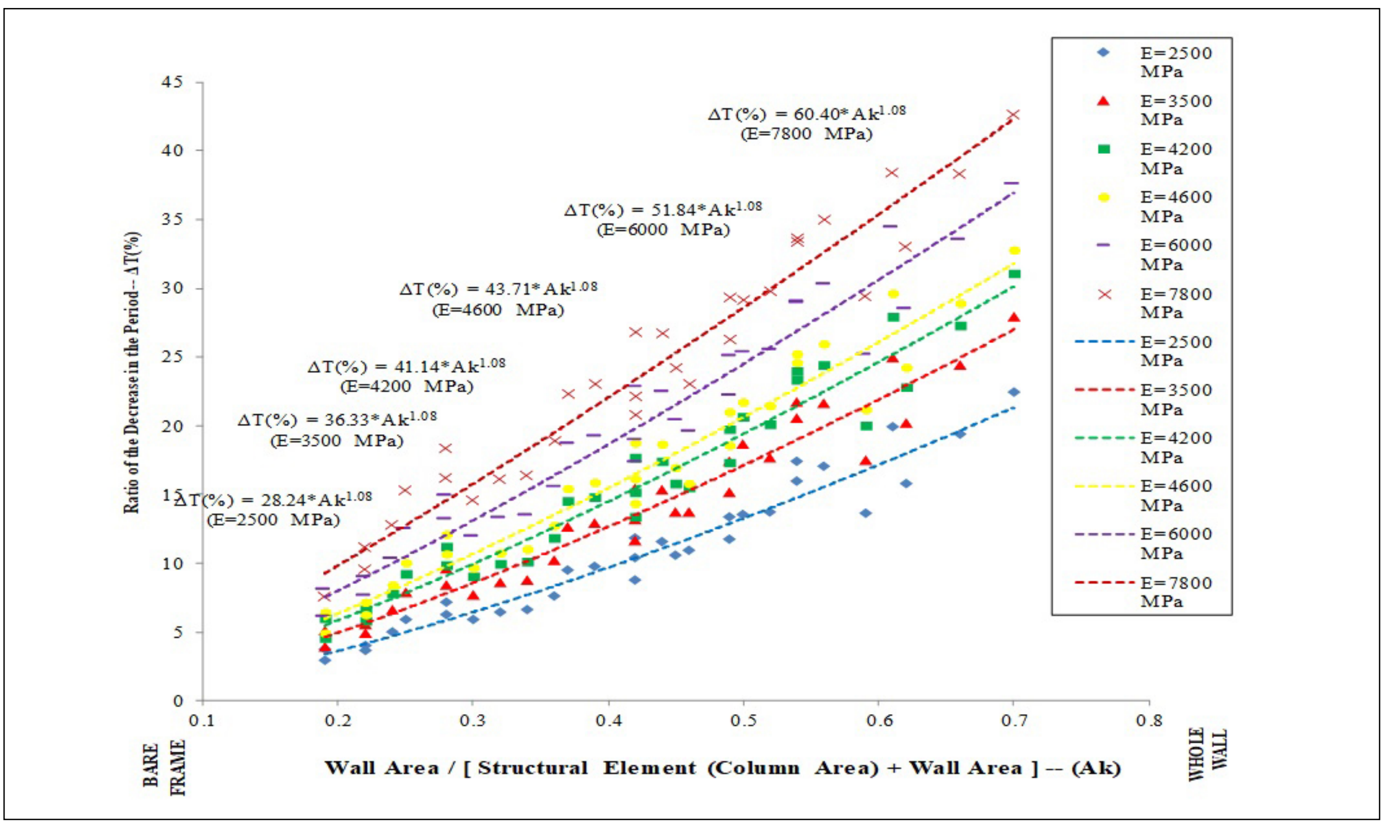


Figure 6. Relationship between ratio of decrease in the period (%) for various infill wall modulus of elasticity values and for 40% β decrease and wall area / [structural element (column area) + wall area].

opening ratio and a=57.259 $E^{-0.465}$ for 80% increase in wall opening ratio.

Table 6 shows the period values obtained in the numerical model for all wall configurations for every modulus of elasticity and for both increasing and decreasing values of the opening ratio.

In addition to the wall configurations mentioned in Table 6, the k coefficient values and Modulus of Elasticities for various wall thicknesses are shown in Table 7.

From the numerical presentation, above, the effect of infill wall thickness to period is around 9-27%. Similarly, the effect of infill wall modulus of elasticity to fundamental building vibration period is around 6-35%; the opening ratio of doors and windows in infill walls for decreasing building periods is around 7-32% and for increasing building periods is around 9-71%. Table 8 shows the results for the obtained period values for tests done on existing buildings and for corresponding buildings and for other empirical relations. The relations obtained by changing the modulus of elasticity of infill wall and infill wall opening ratios verify the measured period values for E = 6000 MPa, and for D4 and D5 type opening ratios as shown in Table 8. The period values for various opening ratios and modulus of elasticity for the corresponding existing buildings can also be found in Figure 8 through Figure 12.

4. Conclusion

The study shows that the infill wall thickness, the modulus of elasticity of the infill walls and the opening ratio off the walls affect the fundamental vibration period of the building.

- The wall thickness affects the fundamental period of the structure by 9%-27%. The lower limit and upper limit of the k_t coefficient in the equation are 68.23 and 69.29 consecutively.
- The increase in the modulus of elasticity decrease the periods by 6%-35%. The lower limit and upper limit of the k_E coefficient in the equation are 41 and 78.53 consecutively.
- The increase of the opening ratio in the walls increase the period by 9%-71% and decrease of the opening ratio

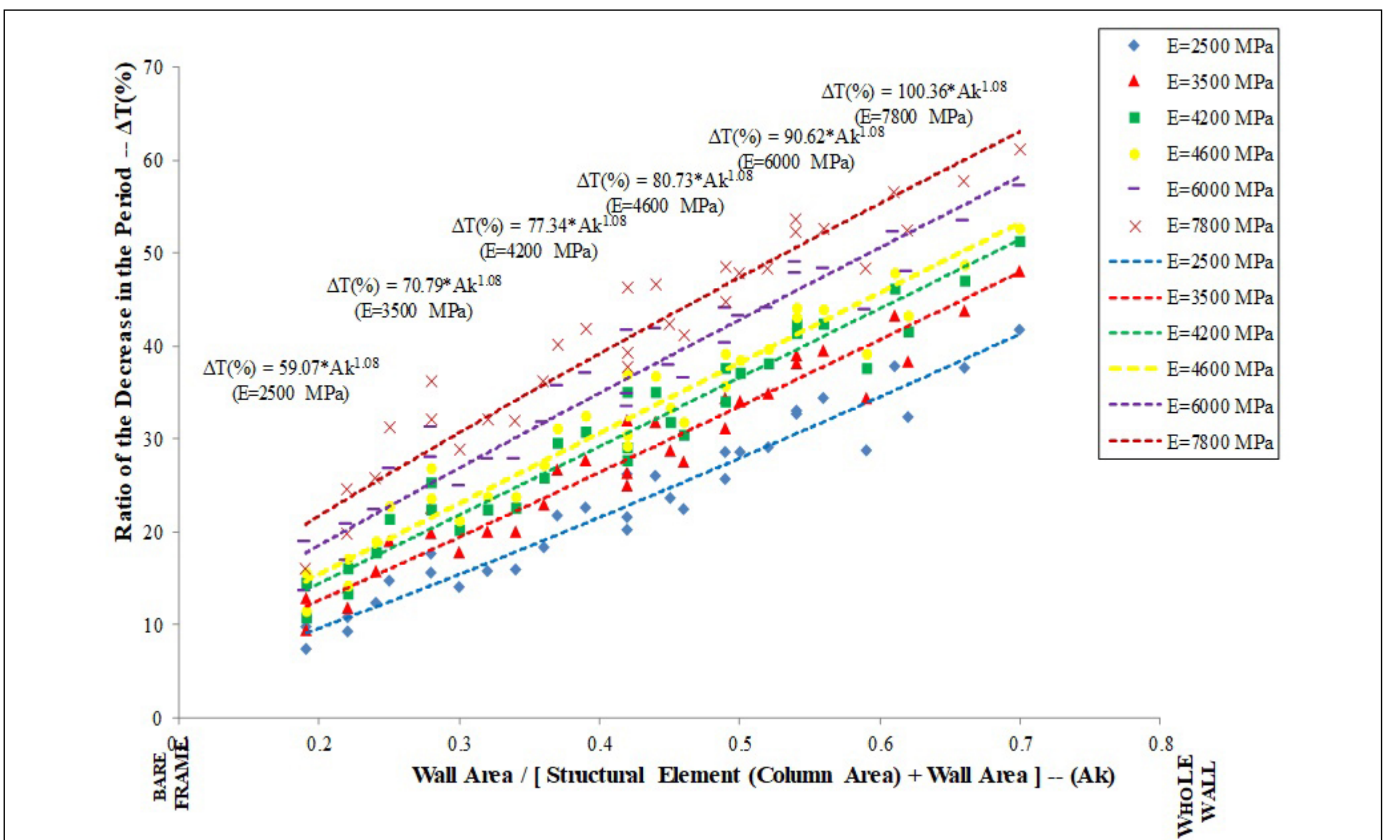


Figure 7. Relationship between ratio of decrease in the period (%) for various infill wall modulus of elasticity values and for 40 % β increase and wall area / [structural element (column area) + wall area].

Table 6. Effect of infill wall opening ratio on building period.

Number of Storeys	Opening Ratio	Period	Modulus of elasticity						D4-D5 Type Change in Opening Ratio (%)
			E = 2500 MPa	E = 3500 MPa	E = 4200 MPa	E = 4600 MPa	E = 6000 MPa	E = 7800 MPa	
3 Storey			$Td = Tc.(1- k_W.Ak^{1.08}/100)$						
	40% decrease in opening Ratio		$k_W = 50.94$	$k_W = 62.00$	$k_W = 68.30$	$k_W = 71.54$	$k_W = 81.26$	$k_W = 90.97$	
		Tx	0.311	0.275	0.255	0.244	0.213	0.181	%9 - %18 Decrease
		Ty	0.302	0.270	0.252	0.243	0.215	0.187	
	Window – Door opening (D4-D5 Type)		$k_W = 41.00$	$k_W = 50.94$	$k_W = 56.79$	$k_W = 59.82$	$k_W = 69.10$	$k_W = 78.53$	
		Tx	0.343	0.311	0.292	0.282	0.252	0.222	---
		Ty	0.330	0.302	0.285	0.276	0.250	0.223	
	40% increase in opening Ratio		$k_W = 28.24$	$k_W = 36.33$	$k_W = 41.14$	$k_W = 43.71$	$k_W = 51.84$	$k_W = 60.40$	
		Tx	0.385	0.358	0.343	0.334	0.308	0.280	%11 - %26 Increase
		Ty	0.366	0.343	0.330	0.322	0.299	0.275	
6 Storey			$Td = Tc.(1- k_W.Ak^{1.08}/100)$						
	40% decrease in opening Ratio		$k_W = 50.94$	$k_W = 62.00$	$k_W = 68.30$	$k_W = 71.54$	$k_W = 81.26$	$k_W = 90.97$	
		Tx	0.538	0.482	0.450	0.434	0.384	0.335	%8 - %16 Decrease
		Ty	0.518	0.469	0.441	0.426	0.383	0.340	
	Window – Door opening (D4-D5 Type)		$k_W = 41.00$	$k_W = 50.94$	$k_W = 56.79$	$k_W = 59.82$	$k_W = 69.10$	$k_W = 78.53$	
		Tx	0.589	0.538	0.509	0.493	0.446	0.398	---
		Ty	0.562	0.518	0.492	0.478	0.437	0.395	
6 Storey	40% increase in opening Ratio		$k_W = 28.24$	$k_W = 36.33$	$k_W = 41.14$	$k_W = 43.71$	$k_W = 51.84$	$k_W = 60.40$	
		Tx	0.654	0.613	0.588	0.575	0.534	0.490	%11 - %26 Increase
		Ty	0.619	0.583	0.561	0.550	0.514	0.476	
9 Storey			$Td = Tc.(1- k_W.Ak^{1.08}/100)$						
	40% decrease in opening Ratio		$k_W = 50.94$	$k_W = 62.00$	$k_W = 68.30$	$k_W = 71.54$	$k_W = 81.26$	$k_W = 90.97$	
		Tx	0.722	0.654	0.615	0.595	0.535	0.475	%8 - %14 Decrease
		Ty	0.665	0.606	0.573	0.556	0.505	0.453	
	Window – Door opening (D4-D5 Type)		$k_W = 41.00$	$k_W = 50.94$	$k_W = 56.79$	$k_W = 59.82$	$k_W = 69.10$	$k_W = 78.53$	
		Tx	0.784	0.722	0.686	0.667	0.610	0.552	---
		Ty	0.717	0.665	0.634	0.618	0.569	0.519	
	40% increase in opening Ratio		$k_W = 28.24$	$k_W = 36.33$	$k_W = 41.14$	$k_W = 43.71$	$k_W = 51.84$	$k_W = 60.40$	
		Tx	0.863	0.813	0.783	0.767	0.717	0.664	%9 - %24 Increase
		Ty	0.785	0.742	0.717	0.703	0.660	0.615	
11 Storey			$Td = Tc.(1- k_W.Ak^{1.08}/100)$						
	40% decrease in opening Ratio		$k_W = 50.94$	$k_W = 62.00$	$k_W = 68.30$	$k_W = 71.54$	$k_W = 81.26$	$k_W = 90.97$	
		Tx	0.819	0.747	0.706	0.685	0.622	0.559	%7 - %13 Decrease
		Ty	0.784	0.722	0.687	0.669	0.614	0.560	
11 Storey	Window – Door opening (D4-D5 Type)		$k_W = 41.00$	$k_W = 50.94$	$k_W = 56.79$	$k_W = 59.82$	$k_W = 69.10$	$k_W = 78.53$	
		Tx	0.884	0.819	0.781	0.762	0.701	0.640	---
		Ty	0.840	0.784	0.751	0.734	0.682	0.629	
	40% increase in opening Ratio		$k_W = 28.24$	$k_W = 36.33$	$k_W = 41.14$	$k_W = 43.71$	$k_W = 51.84$	$k_W = 60.40$	
		Tx	0.967	0.914	0.883	0.866	0.814	0.758	%9 - %19 Increase
		Ty	0.912	0.866	0.839	0.825	0.779	0.731	

in the walls decrease the period by 7%-32%. The lower limit and the upper limit of the k coefficient for β = %40 decrease of the opening is 28.24% and 60.40%, the lower limit and the upper limit of the k coefficient for β = %80 decrease of the opening is 11.24% and 29.73%, the lower limit and the upper limit of the k coefficient for β = %40 increase of the opening is 50.94% and 90.97%, and the lower limit and the upper limit of the k coefficient for β = %80 increase of the opening is 59.07% and 100.36%.

As a result, the equations in the current codes should be modified by considering the modulus of elasticity of the infill walls and the opening ratio of the infill walls or these parameters should be taken into account while calculating the periods of the structure.

Table 7. k coefficient values for infill wall parameters.

Wall Thickness		Modulus of elasticity		Opening Ratio β = %40decrease		Opening Ratio β = %80 decrease		Opening Ratio β = %40 increase		Opening Ratio β = %80 increase	
T (cm)	k_t	E(MPa)	k_E	E(MPa)	k_w	E(MPa)	k_w	E(MPa)	k_w	E(MPa)	k_w
10	69.10	7800	78.53	7800	60.40	7800	29.73	7800	90.97	7800	100.36
15	68.23	6000	69.10	6000	51.84	6000	23.79	6000	81.26	6000	90.62
20	68.57	4600	59.82	4600	43.71	4600	19.12	4600	71.54	4600	80.73
25	68.96	4200	56.79	4200	41.14	4200	17.68	4200	68.30	4200	77.34
30	69.29	3500	50.94	3500	36.33	3500	15.12	3500	62.00	3500	70.79
		2500	41	2500	28.24	2500	11.24	2500	50.94	2500	59.07

H: 14.25 m

TOLGAHAN Apartment			T_X (s)	T_Y (s)
Measured Values		Bare Frame	0.489	0.412
		Infill Wall	0.342	0.271
Kocak & Yıldırım 2011		$T_d = T_c(1 - k_E \cdot Ak^{1.08}/100)$, $k_E = 69.10$	0.333	0.268
This Study	Effect of Opening Ratio at Infill Walls (E = 6000 Mpa)	k_W = 81.26, %40 Decrease at infill wall opening ratio	0.309	0.247
		k_W = 90.62, %80 Decrease at infill wall opening ratio	0.288	0.228
		k_W = 51.84, %40 Increase at infill wall opening ratio	0.374	0.307
		k_W = 23.79, %80 Increase at infill wall opening ratio	0.436	0.364
	Effect of Young Modulus at Infill Walls (D4-D5)	k_E = 41.00, E = 2500 Mpa	0.398	0.329
		k_E = 50.94, E = 3500 Mpa	0.376	0.308
		k_E = 56.79, E = 4200 Mpa	0.363	0.297
		k_E = 59.82, E = 4600 Mpa	0.357	0.290
		k_E = 69.10, E = 6000 Mpa	0.333	0.268
		k_E = 78.53, E = 7800 Mpa	0.315	0.252
Güler et al. 2008		$T_d = 1.75(0.026H^{0.9})$	0.497	
TSC 1998		$T_d = C_t H^{3/4}$	0.513	
UBC 1997		$T_d = Ct(h_N)^{3/4}$	0.536	
Goel and Chopra		$T_{LC} = 0.047H^{0.9}$	0.513	
		$T_{UC} = 0.067H^{0.9}$	0.732	

Figure 8. Effect of infill wall opening ratio and infill wall elasticity modulus to fundamental vibration period of a building.

H: 17.10 m

ENVER PARLAK Apartment

			Tx (s)	Ty (s)
Measured Values		Bare Frame	0.482	0.532
		Infill Wall	0.295	0.376
Koçak & Yıldırım 2011		$T_d = T_c.(1- k_E.Ak^{1.08}/100)$ $k_E = 69.10$	0.296	0.370
This Study	Effect of Opening Ratio at Infill Walls (E = 6000 Mpa)	$k_W = 81.26$, %40 Decrease at infill wall opening ratio	0.269	0.345
		$k_W = 90.62$, %80 Decrease at infill wall opening ratio	0.244	0.324
		$k_W = 51.84$, %40 Increase at infill wall opening ratio	0.346	0.413
		$k_W = 23.79$, %80 Increase at infill wall opening ratio	0.420	0.477
	Effect of Young Modulus at Infill Walls (D4-D5)	$k_E = 41.00$, E = 2500 Mpa	0.374	0.438
		$k_E = 50.94$, E = 3500 Mpa	0.348	0.415
		$k_E = 56.79$, E = 4200 Mpa	0.333	0.401
		$k_E = 59.82$, E = 4600 Mpa	0.325	0.394
		$k_E = 69.10$, E = 6000 Mpa	0.296	0.370
		$k_E = 78.53$, E = 7800 Mpa	0.276	0.351
Güler et al. 2008		$T_d = 1.75(0.026H^{0.9})$	0.585	
TSC 1998		$T_d = C_tH^{3/4}$	0.588	
UBC 1997		$T_d = C_t(h_N)^{3/4}$	0.614	
Goel and Chopra		$T_{LC} = 0.047H^{0.9}$	0.605	
		$T_{UC} = 0.067H^{0.9}$	0.862	

Figure 9. Effect of infill wall opening ratio and infill wall elasticity modulus to fundamental vibration period of a building.

H: 17.50 m

KOÇYİĞİT Apartment

			Tx (s)	Ty (s)
Measured Values		Bare Frame	0.362	0.315
		Infill Wall	0.314	0.232
Koçak & Yıldırım 2011		$T_d = T_c.(1- k_E.Ak^{1.08}/100)$ $k_E = 69.10$	0.303	0.226
This Study	Effect of Opening Ratio at Infill Walls (E = 6000 Mpa)	$k_W = 81.26$, %40 Decrease at infill wall opening ratio	0.293	0.212
		$k_W = 90.62$, %80 Decrease at infill wall opening ratio	0.285	0.200
		$k_W = 51.84$, %40 Increase at infill wall opening ratio	0.318	0.249
		$k_W = 23.79$, %80 Increase at infill wall opening ratio	0.342	0.285
	Effect of Young Modulus at Infill Walls (D4-D5)	$k_E = 41.00$, E = 2500 Mpa	0.327	0.263
		$k_E = 50.94$, E = 3500 Mpa	0.319	0.251
		$k_E = 56.79$, E = 4200 Mpa	0.314	0.243
		$k_E = 59.82$, E = 4600 Mpa	0.311	0.239
		$k_E = 69.10$, E = 6000 Mpa	0.303	0.226
		$k_E = 78.53$, E = 7800 Mpa	0.296	0.216
Güler et al. 2008		$T_d = 1.75(0.026H^{0.9})$	0.598	
TSC 1998		$T_d = C_tH^{3/4}$	0.598	
UBC 1997		$T_d = C_t(h_N)^{3/4}$	0.624	
Goel and Chopra		$T_{LC} = 0.047H^{0.9}$	0.617	
		$T_{UC} = 0.067H^{0.9}$	0.880	

Figure 10. Effect of infill wall opening ratio and infill wall elasticity modulus to fundamental vibration period of a building.

H: 17.70 m

PEMBE KÖŞK Apartment			T_X (s)	T_Y (s)
Measured Values		Bare Frame	0.552	0.489
		Infill Wall	0.396	0.335
Kocak & Yıldırım 2011		$T_d = T_c.(1- k_E .A_k^{1.08}/100)$, $k_E = 69.10$	0.412	0.347
This Study	Effect of Opening Ratio at Infill Walls (E = 6000 Mpa)	$k_W = 81.26$, %40 Decrease at infill wall opening ratio	0.390	0.325
		$k_W = 90.62$, %80 Decrease at infill wall opening ratio	0.371	0.306
		$k_W = 51.84$, %40 Increase at infill wall opening ratio	0.448	0.385
		$k_W = 23.79$, %80 Increase at infill wall opening ratio	0.505	0.441
	Effect of Young Modulus at Infill Walls (D4-D5)	$k_E = 41.00$, E = 2500 Mpa	0.470	0.406
		$k_E = 50.94$, E = 3500 Mpa	0.450	0.386
		$k_E = 56.79$, E = 4200 Mpa	0.439	0.375
		$k_E = 59.82$, E = 4600 Mpa	0.433	0.368
		$k_E = 69.10$, E = 6000 Mpa	0.412	0.347
		$k_E = 78.53$, E = 7800 Mpa	0.395	0.331
Güler et al. 2008		$T_d = 1.75(0.026H^{0.9})$	0.604	
TSC 1998		$T_d = C_t H^{3/4}$	0.604	
UBC 1997		$T_d = C_t(h_N)^{3/4}$	0.631	
Goel and Chopra		$T_{LC} = 0.047H^{0.9}$	0.624	
		$T_{UC} = 0.067H^{0.9}$	0.889	

Figure 11. Effect of infill wall opening ratio and infill wall elasticity modulus to fundamental vibration period of a building.

H: 15.75 m

ŞAHİNER Apartment			T_X (s)	T_Y (s)
Measured Values		Bare Frame	0.521	0.411
		Infill Wall	0.358	0.291
Kocak & Yıldırım 2011		$T_d = T_c.(1- k_E .A_k^{1.08}/100)$, $k_E = 69.10$	0.370	0.283
This Study	Effect of Opening Ratio at Infill Walls (E = 6000 Mpa)	$k_W = 81.26$, %40 Decrease at infill wall opening ratio	0.347	0.263
		$k_W = 90.62$, %80 Decrease at infill wall opening ratio	0.326	0.246
		$k_W = 51.84$, %40 Increase at infill wall opening ratio	0.410	0.317
		$k_W = 23.79$, %80 Increase at infill wall opening ratio	0.470	0.368
	Effect of Young Modulus at Infill Walls (D4-D5)	$k_E = 41.00$, E = 2500 Mpa	0.433	0.336
		$k_E = 50.94$, E = 3500 Mpa	0.412	0.318
		$k_E = 56.79$, E = 4200 Mpa	0.399	0.308
		$k_E = 59.82$, E = 4600 Mpa	0.393	0.302
		$k_E = 69.10$, E = 6000 Mpa	0.370	0.283
		$k_E = 78.53$, E = 7800 Mpa	0.352	0.268
Güler et al. 2008		$T_d = 1.75(0.026H^{0.9})$	0.543	
TSC 1998		$T_d = C_t H^{3/4}$	0.553	
UBC 1997		$T_d = C_t(h_N)^{3/4}$	0.578	
Goel and Chopra		$T_{LC} = 0.047H^{0.9}$	0.561	
		$T_{UC} = 0.067H^{0.9}$	0.800	

Figure 12. Effect of infill wall opening ratio and infill wall elasticity modulus to fundamental vibration period of a building.

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