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APPROACHES OF INFILL WALL MODELING IN FRAME SYSTEMS

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ABSTRACT

It is known that infill walls considerably alter the behavior of frames under lateral loads. However, the effects of infill wall materials on building strength are mostly neglected. Structural fractures are initiated first in key structural members including infill walls. Therefore, behaviors of infilled frame systems should be analyzed and well-comprehended. In this study, two-story tree-span frame systems with/without infill walls and with/without shear walls were modeled with the aid of equivalent diagonal compression strut and finite element methods. Present findings revealed that infill walls had significant effects on building rigidity, period, lateral displacements, shear forces and behaviors.

KEYWORDS: Infill walls, earthquake analysis, brick, equivalent diagonal compression strut model, rigidity.

1. INTRODUCTION:

In general, load-bearing effects of infill walls under lateral loads are quite well-known, but they are usually neglected. The observations and investigations on earthquake-induced damages on buildings revealed that infill walls provided significant contributions to rigidity, load bearing capacity, period and damping-like dynamic attributes of the buildings with significant effects on long-term durability and on-purpose service of the buildings. In conventional design and calculations for infill walls, contributions of the wall are neglected and such a negligence mostly attributed to great variety in infill wall materials and the resultant variety in strength and lack of in-field inspections. Structural or non-structural cracks are initiated over any key structural members at capillary levels or they are initiated over a large area through various reasons. Then, as a result of these cracks against which the measures were not taken or were not able to be taken, partial or overall failure is observed in buildings. Therefore, behavior of every member constituting a building should be known. During the earthquakes, generally great damages and fracture mechanisms are clearly visible on infill walls. Previous theoretical and empirical studies on behavior of infill walls under earthquake loads revealed contrary to actual cases that infill walls greatly influenced earthquake behavior of the buildings. With proper design and workmanship, infill walls may improve building resistance against not only especially the vertical loads, but also the lateral loads. However, improper design and negligence may result in negative cases influencing collapse mechanisms of the building. Therefore, the behavior of infill walls should be well-comprehended to improve positive impacts of infill wall members and turn them into structural members with great contributions to bearing capacity instead of being dead loads. In this study, two-story three-span frame systems with/without shear walls and with/without infill walls were modeled with the aid of equivalent diagonal compression strut and finite element methods and the effects of different modulus of elasticity values on building behavior and strength were investigated. Analyses were performed based on 2007 Earthquake Regulations of Turkey and changes in period, shear force and displacement values influencing building behavior were investigated.

2. THEORY AND METHOD:

2.1. Effects of Infill Walls on Building Behavior:

There are several studies in literature about the behaviors of frame systems with/without infill walls under lateral loads. In a previous study investigating building behavior under lateral loads, experiments were conducted to determine the behavior of an infill wall of a composite frame system under lateral loads and it was reported that the concrete frame with infill walls exhibited at least two times greater load bearing capacity than the frames without infill walls and infill walls significantly improved building elasticity and rigidity (Govindan et al., 1986). In another study, in cases where infill wall was created as macrovoid and low strength, the frame system with infill wall provided at least 40% greater contribution to lateral load bearing capacity as compared to frame system without an infill wall (Vintzeleou, 1989). It was observed in a later study that lateral load bearing capacity of a building with infill walls was about 1.5 times greater than the lateral load bearing capacity of a building without infill walls, a soft-story concrete building and a concrete building without infill walls exhibited similar behaviors with regard to lateral load bearing capacity (Negro and Verzeletti, 1996). In Turkey, ground floors are generally used as work place or office. Therefore, partition walls do not generally exist in ground floors. Then, the upper floors behave more rigid because of the partition walls (considering they behave like a shear wall until the incidence of an earthquake). Since the entire energy consumption is concentrated at the ground floor, a soft-story is formed in such buildings and damages are experienced then. Unexpected excessive damages are generated over the columns of these floors without infill walls and such a case mostly end up with total collapse of the buildings. Since the earthquake energy is confronted in this floor, rigidity of the columns and shear walls of this floor should be improved as to bear inter-floor displacements. Soft-story is formed generally because of static bearing system or partition walls. If the walls are constructed short and connected to frames, then the columns of the main frame cannot bend in between two stories they connected under lateral forces of an earthquake because of the rigidity of the walls along their own planes. In this case, columns are forced to bend over the section with the empty height left over the upper sections of the walls. Then quite greater shear forces are generated over this section of the columns (Çağatay,2007). The windows extending from wall to wall then generate a short-column effect and thus reduce column length. Short-column formation is defined as the reduction in column length and resultant increase in shear forces. Stirrup frequency should be increased to bear resultant shear forces and wall-to-wall windows should not be preferred as much as possible. Experimental works on frames and buildings with infill walls revealed that door and window spaces left over these members reduce building rigidity and generate damages on buildings (Zarnic and Tomasevic, 1995; Koçak, 1998).

2.2. Materials Used in Infill Walls of Concrete Structures:

Brick is the most common material used in infill walls of concrete structures. Bricks are produced as solid bricks, hallow bricks, pressed bricks and etc for various purposes. Horizontally perforated bricks with greater hallow ratios were used since they have low compression strength when they were loaded vertical to hallows. Specifications for horizontally perforated bricks are provided in Table 1.

Table 1. Specifications of horizontally perforated bricks

Specification	8.5 Horizontally perforated bricks	13.5 Horizontally perforated bricks
Height x Width x Length (cm)	8.5 x 19 x 19	13.5 x 19 x 19
Mean Compressive Strength (MPa)	4	5.2
Weight of single brick (kg)	2	3
Number of bricks per m^2	25	25 and 33

2.3. Modules of Elasticity for Infill Wall Materials:

Effects of infill wall behaviors on frame systems largely depend on wall rigidity and modulus of elasticity play a great role in wall rigidity. Infill walls are not homogeneous members and they have different modulus elasticity values in different directions (horizontal, vertical, diagonal). There are several studies in literature indicating that modulus of elasticity varied with the compressive strength of the material, height, compressive strength of mortar layer and height of mortar layer (Bilir Özhan and Çağatay, 2014). Modules of elasticity of infill walls are also different for plastered and unplastered walls. Plaster thickness also alters modulus of elasticity. In this sense, modulus of elasticity values of brick walls in different studies are provided in Table 2 where Ed expresses the modulus of elasticity of the wall under compression and E_c expresses the modulus of elasticity of concrete under compression.

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Table 2. Modules of elasticity values for brick walls

Literature	E_d (MPa)	E_c (MPa)	E_d / E_c
(Aydoğdu, 1995)	5200	30000	1/6
(Yalçın, 1999)	1240	30000	1/24
(Çağatay, 2002)	2850	28500	1/10
(Öktem, 2003)	6000	12000	1/2
(Dündar, 2006)	700	25310	1/36
(Budak, 1997)	17000	28500	1/1.7
(Dönmez, 2006)	3000	32000	1/10
(TDY, 2007)	1000	-	-

2.4. Equivalent Diagonal Compression Strut Model:

Several studies have been performed to determine and elucidate the linear behaviors of infill walls (Smith and Carter, 1969; Mainstone, 1974) and they generally reported diagonal cracks at the center of modeled panel, voids between the frame and infill at opposite unloaded corners of the model and a full contact at the other two loaded diagonal corners. To reflect such behaviors on actual infill walls and to facilitate the analysis of infill wall frame systems, infill walls were placed as equivalent compression struts (Figure 1).

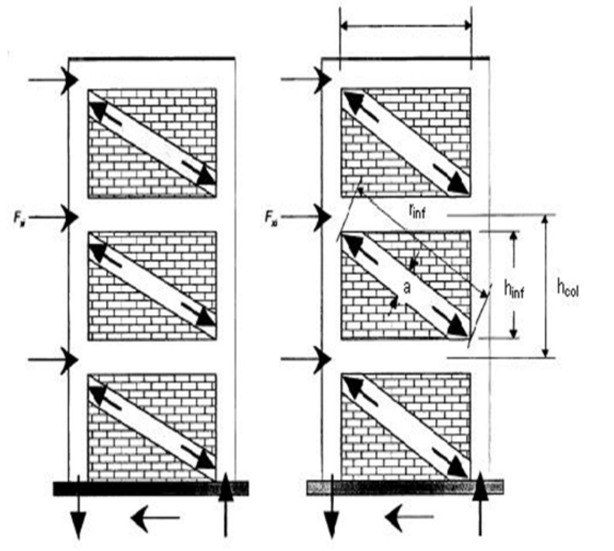

Figure 1. Representation of infill wall in analysis model (Fema 273,1997)

The compressive load-bearing region was represented with an equivalent virtual bar in static analysis of frame systems under external forces (Figure 2).

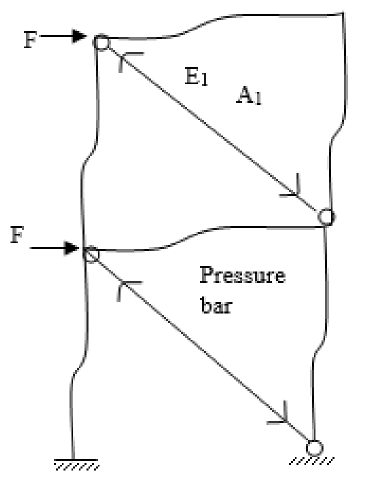

Figure 2. Representation of infill wall frames with two end-hinged equivalent virtual diagonal bar

Different researchers used different assumptions in calculating the thickness of equivalent diagonal struts (Smith and Carter, 1969; Mainstone, 1974; FEMA - 306, 307-356) and proposed the equations (1), (2) and (3) for strut thickness:

$$a = 0{,}175(\lambda_1 h_{col})^{-0{,}4} r_{inf} \tag{1}$$

$$\lambda_1 = \left[\frac{E_{me} t_{inf} \sin 2\theta}{4 E_{fe} I_{col} h_{inf}}\right]^{\frac{1}{4}} \tag{2}$$

$$\theta = \tan^{-1}\left(\frac{h_{inf}}{L_{inf}}\right) \tag{3}$$

Where; h_{col} = Column height , h_{inf} = Infill wall height, E_{fe} =Modulus of elasticity of the frame material, E_{me} = Modulus of elasticity of the infill wall material, I_{col} = Moment of inertia of the columns, L_{inf} = Infill wall length, r_{inf} = Infill wall length of diagonal, t_{inf} = Thickness of the infill wall, λ_1 = Coefficient used to calculate the equivalent width of the pressure bar.

2.5. Finite Element Mesh Models:

Plane fill system is assumed to be a continuum and the system is modeled with two-dimensional triangles or rectangular (Figure 3). With this modeling approach, the system emerges as a high-degree statically indeterminate plane stress problem composed of finite number of elements (one or more) fulfilling the equilibrium and continuity conditions only at node points. Such an approach is solved in computer environment and provides full compatibility between the infill and the frame (Sayın, 2003).

In fine element modeling, for accurate representation of the effects of infill wall to the frame system, there should not be any empty spaces in practice between the members constituting infill wall, these members should be jointed to each other with mortar and the frame system- infill wall connection should be well-established for full load transfer.

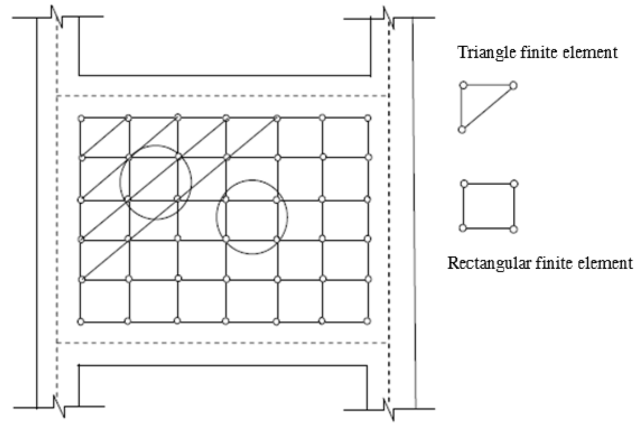

Figure 3. Finite element modeling of the infill plane within the frame system with triangular or rectangular members

3. INVESTIGATED FRAME SYSTEMS:

3.1. Two-story three-span frame system:

The effects of infill walls on structural irregularities were modeled with a two-story tree-span frame system through applying 5 and 10 t forces.

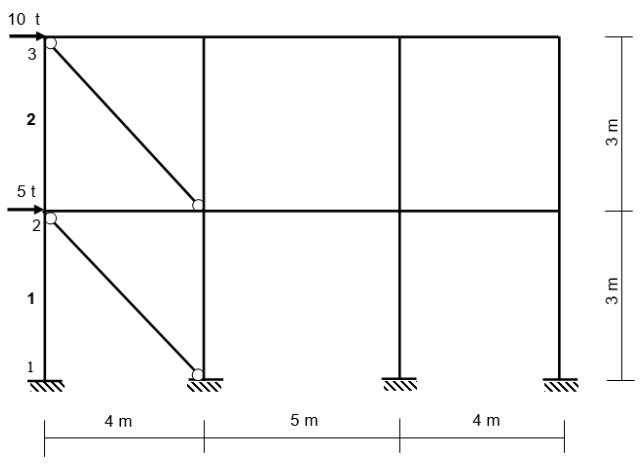

Figure 4. Two-story and three-span frame models

Data:
Wall Thickness (Brick) : 10 cm
Beam Dimensions : 25 x 45 cm
Column Sizes : 40 x 40 cm
Concrete Class : C20
Concrete Modules of Elasticity (Ec) : 28500 MPa
Brick Wall Modules of Elasticity (Ed-1) : 1000 MPa
Brick Wall Modules of Elasticity (Ed-2) : 2850 MPa

Table 3. Displacement Values of Two-Story and Three-Span Frame

Point number	E(1)		E(2)	
	Without infill wall	With infill wall	Without infill wall	With infill wall
	1	2	1	2
	Displacement (mm)			
1	0	0	0	0
2	5,84	4,57	5,84	3,34
3	15,11	11,30	15,11	7,85

Table 4. Moment Strength Values (M_{33}) of Two Story and Three Span Frames

Member number	Member length (m)	(M_{33}) Moment Strength Values (t-m)		
		Without infill wall (E-1)	With infill wall (E-1)	With infill wall (E-2)
1	0	12,34	9,93	7,50
	3	-1,36	-1,64	-1,67
2	0	-5,88	3,20	1,67
	3	5,11	-4,17	-2,67

When the point displacements of empty frame and infill wall frame systems were compared (Table 4), it was observed that there was a decrease in displacements by 22.3% at point 2 and by 25.0% at point 3. When these values were compared to changes in their modulus of elasticity, it was observed that displacements decreased with increasing modulus of elasticity. When the frame systems with and without infill walls were compared, a decrease of 43.3% was observed at point 2 and 48.0% at point 3.

Table 5. Shear force values (V_{22}) of two-story and three-span frame

Member number	Member length (m)	V_{22} Shear Force (t)		
		Without infill wall (E-1)	With infill wall (E-1)	With infill wall (E-2)
1	0	4,57	3,86	3,06
	3	4,57	3,86	3,06
2	0	3,67	2,46	1,45
	3	3,67	2,46	1,45

3.2. Two-story three-span shear wall plane frame:
Two-story three-span shear wall plane frame was loaded with 5 and 10 t forces and the effects of infill wall on frame system were investigated.

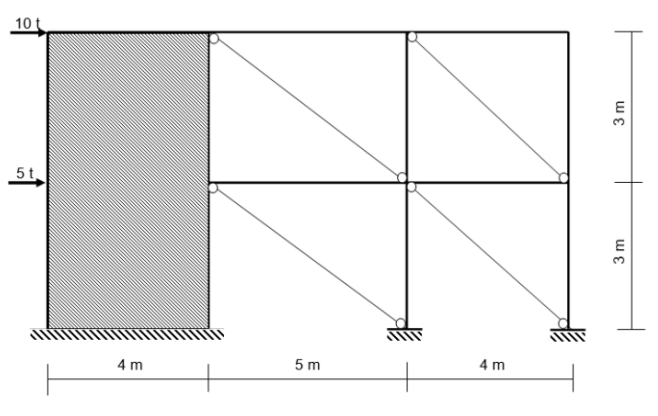

Figure 5. Two-story and three-span shear wall frame models

Data:
Wall Thickness (Brick) : 10 cm
Shear wall Thickness : 25 cm
Beam Dimensions : 25 x 45 cm
Column Sizes : 40 x 40 cm
Concrete Class : C20
Concrete Modules of Elasticity (Ec) : 28500 MPa
Brick Wall Modules of Elasticity (Ed-1) : 1000 MPa
Brick Wall Modules of Elasticity (Ed-2) : 2850 MPa

Table 6. Displacement values of two-story and three-span shear wall frames

Point Number	E(1)			E(2)		
	Without infill wall	With infill wall	Finite Element	Without infill wall	With infill wall	Finite Element
	1	2	3	1	2	3
	Displacement (mm)					
1	0,00	0,00	0,00	0,00	0,00	0,00
2	0,16	0,17	0,14	0,16	0,17	0,11
3	0,41	0,39	0,33	0,41	0,36	0,24

When the point displacements of empty and finite element frame systems were compared, it was observed that there was an increase of 1.22% and a decrease of 16.43% at point 2 and there was a decrease of 4.19% and 19.705 at point 3. When these values were compared to changes in their modulus of elasticity, it was observed that displacements decreased with increasing modulus of elasticity. When the frame systems with and without infill walls were compared, an increase of 1.83% and a decrease of 32.3% was observed at point 2 and a decrease of 10.59% and 41.13% was observed as point 3.

Table 7. Moment strength values (M_{33}) of two-story and three-span shear wall frame

Member Number	Member Length (m)	(M_{33}) Moment Strength Values (t-m)				
		Without infill wall (E-1)	With infill wall (E-1)	Finite Element (E-1)	With infill wall (E-2)	Finite Element (E-2)
1	0	0,36	0,37	0,32	0,39	0,26
	3	-0,06	-0,08	0,08	-0,12	-0,08
2	0	0,12	0,09	0,07	0,04	0,03
	3	-0,15	-0,01	-0,11	-0,11	-0,07

Table 8. Shear force values (V_{22}) of two-story and three-span shear wall frame

Member Number	Member Length (m)	V_{22} Shear Force (t)				
		Without infill wall (E-1)	With infill wall (E-1)	Finite Element (E-1)	With infill wall (E-2)	Finite Element (E-2)
1	0	0,14	0,15	0,13	0,17	0,12
	3	0,14	0,15	0,13	0,17	0,12
2	0	0,09	0,07	0,06	0,05	0,03
	3	0,09	0,07	0,06	0,05	0,03

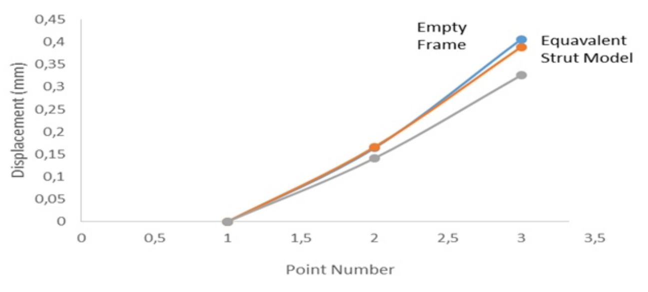

Figure 6. Displacement graphics of two-story and three-span shear wall frame models

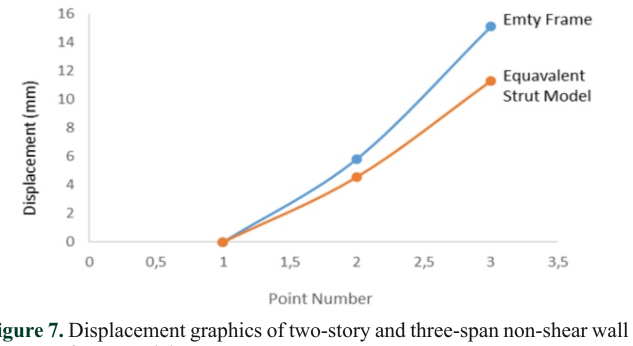

Figure 7. Displacement graphics of two-story and three-span non-shear wall frame models

In the graphics, the infill wall and shear wall frame models were found to be more rigid and they had lower displacement values than the models without a shear wall and infill wall.

4. RESULTS AND DISCUSSION:

In previous studies, modulus of elasticity of brick walls varied between 700 – 17000 MPa and the value was reported as 1000 MPa for hallow bricks (15). In another study, modulus of elasticity was reported as 4272 MPa for high-strength pressed bricks. It was inferred from all these values that brick walls should have a modulus of elasticity of minimum 1000 MPa and maximum 4272 MPa. Concrete classes vary between C20 – C50, thus the modulus of elasticity values of concrete classes calculated for 1/28 – 1/15 vary between 1000 MPa – 2467 MPa. Such a range can be used to select the modulus of elasticity of brick walls in theoretical studies.

In this study, plane frame models with/without infill walls and with/without shear walls were analyzed and changes in displacements and internal forces were investigated. With the modeling of infill wall as an equivalent diagonal compression strut, significant decreases were observed in displacements, moments and shear forces as compared to empty frame system. These values even further decreased in finite element model. It was also observed that use of different modulus of elasticity values had positive effects on decreasing displacement, moment and shear force values. The frame systems with infill walls and shear walls generally exhibit more rigid behaviors than empty frame systems. As compared to infilled and finite element frame models, displacement values increased respectively by 1.22 and 16.43% at point 2 and respectively by 4.19 and 19.70% at point 3 of empty frame model. As compared to empty frame model, respectively 1.83% increase and 32.35 decrease were observed at point 2 and respectively 10.59% and 41.13% decreases were observed at points 3 of infilled frame and finite element frame models.

As to conclude, in places like Turkey where frequent earthquakes are experienced and buildings are exposed to reversible lateral loads, entire characteristics of structural members should be well-comprehended and they should then be designed accordingly. Previous literatures and present analyses revealed that although negative issues in calculations and implementations haven't been elucidated yet, infilled frame systems with great effects on earthquake behavior of the buildings should be included in structural analyses. Frame systems should be modeled and designed as infilled frame systems to get actual behaviors of the buildings in case of an earthquake. Safer and more economic design procedures should be adapted in structural design.

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