Effects of Brick and Aerated Concrete Infill Walls on Buildings

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Abstract—**It has already been proved that infill walls have great impact on the behavior of the frame systems, especially under earthquake-like lateral loads. Infill walls are generally considered as partition members between spaces in concrete frame systems. They are generally included into calculations as dead loads exerted on beams, but they have various impacts on the behavior of frame-wall systems. Therefore, the well-known behavior of infill walls will have positive contributions. In the present study, a 10-story building was modeled with brick and aerated concrete infill walls. Window and door spaces were taken into consideration. Infill walls were modeled with the equivalent compression strut method. Changes in building rigidity, period, lateral displacement, base shear force and building behavior were investigated with relevant analyses.**

Keywords-infill wall; earthquake analysis; brick; aerated concrete; equivalent compression strut

I. INTRODUCTION

Along with increasing sheltering demands, construction industry is continuously growing. However, the available land for construction is not increasing at the same pace, thus high-rise buildings have opted. In this sense, economy and utilization of concrete frame systems have become significant issues of construction industry. Generally, light-weight materials are preferred in such frame systems especially for heat, noise and similar insulations and partition walls are constructed also with these materials to facilitate the utility of building space. Infill walls have significant effects on the bearing-system of the building under lateral loads, therefore, the behavior of these walls under lateral loads, like earthquake loads, should be well elucidated. Negative impacts of such walls are generally attributed to the diverse range of materials, the diversity in their strength, and insufficient inspections of present implementations. In practice, these walls are reflected in calculations as the members increasing only the dead loads of the building and their load-bearing behaviors are generally neglected. Observations and investigations on earthquake damages of the buildings revealed that although infill walls were not considered in calculations made for earthquakes, they resisted to lateral earthquake loads like a shear wall until time of failure. Post-failure behavior of these walls cannot be estimated accurately and they are considered as if they did not exist in calculations. Then, great damages are experienced in practice. The literature on infill walls revealed that infill walls had significant contributions to rigidity, load-bearing capacity, period and damping-like dynamic attributes of the buildings. The structure altogether behaves like a composite material. Therefore, the behavior of each and every single member of the structure should be known. In the present study, a ten-story building was modeled to investigate how effective the infill walls in increasing building resistance to vertical and especially to lateral loads. Bricks and aerated concrete were used in building infill walls. In calculations, the behavior and effects of infill walls with two different materials were investigated.

II. METHODOLOGY

A. Infill Walls

There are several studies about the behavior of frame systems with/without partition walls under earthquake and similar lateral loads. In [1], experiments were conducted to determine the behavior of infill walls under lateral loads and it was reported that the concrete frame with infill walls had greater load-bearing capacity than the frames without infill walls and infill walls significantly improved building elasticity and rigidity behavior. Infill walls are not always formed in fully-filled fashion. There may be empty spaces on them left for different purposes. In cases where the infill wall was created as macro-void, 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 [2]. Similarly, a soft-story concrete building and a concrete building without infill walls exhibited similar behavior with regard to lateral load bearing capacity [3]. In Turkey, ground floors are generally used for purposes other than housing. Ground floor projects are thus generally altered (columns are cut, existing walls are removed etc.). Therefore, partition walls generally do not exist in ground floors. In this case, the upper floors behave more rigid because of the partition walls in comparison with ground floors. Such a case results in concentrated energy consumption on the ground floors. A soft-story is formed in such buildings and destructive damages and failures are experienced in this weaker floor of the building. In other cases, damages are generated over the columns of these floors without infill walls. Since the earthquake energy is confronted in this floor, the rigidity of the

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columns and shear walls of this floor should be improved as to bear inter-floor displacements. If the walls are constructed short and connected to frames, then the columns of the main frame cannot bend in between two stories they connect under lateral forces of an earthquake because of the rigidity of the walls along their own planes. Then a soft-story is formed. 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 [4]. Long windows extending along the both sides of the walls preferred in factory-like buildings generate a short-column effect and reduce the effective length of the column. Experimental works on frames with infill walls revealed that door and window spaces should be avoided on these members and thus building rigidity should be increased to reduce potential damages [5, 6] Confinement of stirrup should be increased to bear resultant shear force.

B. *Brick as Infill Wall Material*

Brick is one of the most commonly used and preferred materials for infill walls of concrete structures. Since the use of two different materials in infill walls is compared in this study, horizontally perforated bricks with greater hallow ratios were used since they have low compression strength. Specifications for horizontally perforated bricks are provided in Table I. While modeling infill walls, 13.5 horizontally perforated bricks were used in exterior walls and 8.5 horizontally perforated bricks were used in interior walls. G2-class aerated concrete was also used as infill wall material. This material is generally used as exterior and interior infill wall material of concrete frame structures or used as load-bearing exterior and interior wall material of masonry structures. They are composed of 70-80% less concrete, and are resistant to earthquake and fires. Specifications for G2-class aerated concrete are provided in Table II.

TABLE I. HORIZONTALLY PERFORATED BRICKS SPECIFICATIONS

Specification	8.5 horizontally perforated bricks	13.5 horizontally perforated bricks
Height×width×length (cm)	8.5×19×19	13.5×19×19
Mean compressive strength (MPa)	4	5.2
Single brick weight (kg)	2	3
Bricks per m^2	25	25 or 33

TABLE II. AERATED CONCRETE SPECIFICATIONS

Specification	For interior walls	For exterior walls
Length×height×width (cm)	60×25×8.5	60×25×19
Mean compressive strength (MPa)	2.5	2.5
Weight of single aerated concrete (kg)	5.1	12
Number of aerated concrete per m^2	6.66	6.66

C. *Modulus of Elasticity*

Infill wall modulus of elasticity significantly influences wall rigidity of frame-wall systems. Infill walls exhibit complex behavior since the modulus of elasticity values in different directions (horizontal, vertical, diagonal) are different. Significant effects of compressive strength of the material, height, compressive strength of mortar layer on the modulus of elasticity are indicated in [7]. It was also indicated that the modulus of elasticity of infill walls was different for plastered and unplastered walls and varied with the thickness of the plaster layer. Modulus of elasticity values of brick walls used in different studies are provided in Table III. In this table, E_w and E_c respectively express the modulus of elasticity of the wall and the concrete under compression.

TABLE III. BRICK WALL MODULUS OF ELASTICITY VALUES

Reference	E_w (MPa)	E_c (MPa)	E_d / E_c
[8]	5200	30000	1/6
[9]	1240	30000	1/24
[10]	2850	28500	1/10
[11]	6000	12000	1/2
[12]	700	25310	1/36
[13]	17000	28500	1/1.7
[14]	3000	32000	1/10
[15]	1000	-	-

In a study carried to determine aerated concrete wall modulus of elasticity values [16], the modulus of elasticity of a wall constructed with A2 class aerated concrete and without plaster was reported as 1500MPa. The modulus of elasticity of a plastered wall was reported as 2091MPa, unit weight was reported as 400kg/m^3 and compressive strength was reported as 2.5MPa. In [17], masonry aerated concrete blocks were cut into 10×10×10cm^3 cubes and 10×10×40cm^3 prisms and their modulus of elasticity values and Poisson ratios were experimentally determined. Resultant values are summarized in Table IV. In [18], modulus of elasticity of aerated concrete of a wall panel was identified as 1750MPa. Specifications of Turkish Aerated Concrete Producers Association for aerated concrete of wall blocks are provided in Table V [2].

TABLE IV. PHYSICAL ATTRIBUTES OF AERATED CONCRETE WALL

Specific gravity (N/m^3)	Mean cube strength (MPa)	Mean prismatic strength (MPa)	Mean initial modulus of elasticity(MPa)	Mean Poisson ratio
7500-8000	4.90	3.32	1620	0.21
9000	4.60	3.08	1570	0.20
8000-8500	3.60	2.64	1490	0.19

TABLE V. AERATED CONCRETE WALL BLOCKS

<table>
<tr><th>Material strength class</th><th colspan="4">A2</th><th colspan="4">A3</th><th colspan="4">A4</th><th>Unit</th></tr>
<tr><td>Mean compressive strength</td><td colspan="4">2.5</td><td colspan="4">3.5</td><td colspan="4">5.0</td><td>MPa</td></tr>
<tr><td>Modulus of elasticity</td><td colspan="3">1250</td><td colspan="3">1750</td><td colspan="3">2250</td><td colspan="3">2750</td><td>MPa</td></tr>
</table>

D. *Equivalent Diagonal Strut Model*

Previous studies conducted to determine and elucidate the linear behaviors of infill walls [19, 20] revealed diagonal cracks at the center of the 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). The compressive load-bearing region was represented with an equivalent diagonal strut in static analysis of frame systems under external forces (Figure 2).

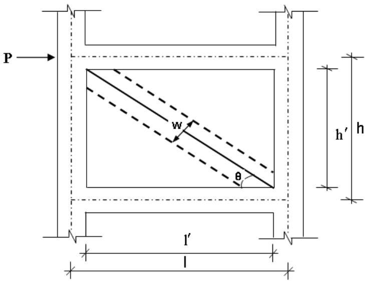

Fig. 1. Representation of infill wall analysis model

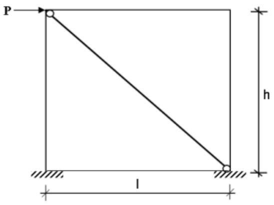

Fig. 2. Representation of infill wall frames with two end-hinged equivalent virtual diagonal bar

Different researchers used different assumptions in calculating the thickness of equivalent diagonal struts. Authors in [19, 20] proposed (1) and (2) for strut width representing the infill wall:

$$w = 0.175\,(\lambda\ h) - 0.4\sqrt{h' + l'} \qquad (1)$$

$$\lambda = \sqrt[4]{\frac{E_m t \sin 2\theta}{4 E_c I_c h'}} \qquad (2)$$

The compressive load-bearing region was represented with an equivalent virtual bar in static analysis of frame systems under external forces (Figure 2). The value of θ used in (2) is calculated with the aid of (3):

$$\theta = \tan^{-1}(h' / l') \qquad (3)$$

where w is the width of equivalent diagonal compression strut, λ is the rigidity parameter of the infill and frame, h the floor height, l the frame span, h' the infill wall height, $l'$the infill wall width, E_m is the modulus of elasticity of equivalent virtual compression strut, t the infill wall thickness, θ the angle of equivalent virtual compression strut from the horizontal plane, E_c the frame modulus of elasticity, and I_c is the column moment of intertia.

E. Partially Infilled Frames

Infill walls are either constructed without openings or they may have window and door spaces. In such a case, equivalent compression strut width is multiplied with a reduction factor to include loss of strength due to these void spaces into calculations [21].

$$W_{reduction} = w\ (R_1)_i (R_2)_i \qquad (4)$$

$$(R_1)_i = 0.6 \times \left(\frac{A_{gap}}{A_{panel}}\right)^2 - 1.6 \times \left(\frac{A_{gap}}{A_{panel}}\right) + 1 \qquad (5)$$

where A_{gap} is the total area of void spaces over the infill wall, A_{panel} is the full area of infill wall without voids, $(R_1)_i$ the expression of reduction factor for infill walls with void spaces, and $(R_2)_r$ the expression of reduction factor for existing infill damages.

In cases where infill walls have window and door spaces, the reduction factor R_1 is applied on the calculations made for the width of equivalent compression strut. In cases where there aren't any damages on infill walls, then R_2 is considered as 1. In cases where there are heavy damages, R_2 can be taken as 0 since the wall will have slight contributions to building rigidity due to breakouts between the frame and the infill wall. In such cases, the wall will contribute only to the weight of the building and will not have any contributions to lateral rigidity.

III. BUILDING MODEL

A building was modeled with two different infill wall materials to investigate their effects on structural irregularities. Total floor height (HN) was 15m and the elasticity level was high. Earthquake analysis of a regular structure was performed with equivalent seismic load method.

TABLE VI. BUILDING INFORMATION

Building Information	
Slab	12cm
Interior wall thickness (brick and aerated concrete)	10cm
Exterior wall thickness (brick and aerated concrete)	20cm
Beam dimensions	25×50 cm
Column dimensions	40×40cm
Concrete class	C30
Concrete modulus of elasticity (Ec)	32000MPa
Brick wall modulus of elasticity (Ew)	1000MPa
Aerated concrete wall modulus of elasticity (Ew)	2091MPa
Number of floors	10
Bearing system type	R.C. Frame
Floor height	3m
Earthquake zone	1
Effective ground acceleration coefficient	0,4
Local ground class	Z3
Spectrum characteristic periods	TA=0.15sn TB=0,60sn

Building ax along x direction are A, B, C, D, E and F and axle spacing was 5m (Figure 3). The axles along y direction are 1, 2, 3 and 4 and ax spacing was 4m, 2m and 4m. Except for the window in the hall, the size of all windows was 150×130cm^2 and the door size was 90×220cm^2. The size of the window at the hall was 100×200cm^2. The building was considered as separated from a-axle with a joint to separate shear wall effect from the building, in this way, the effects of infill wall on the building were analyzed.

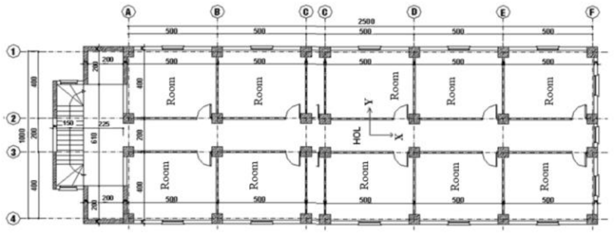

Fig. 3. Building model

The abbreviations for the model are: BEF: empty frame modeled though taking brick wall only as weight, BWF: the frame with brick wall, AEF: empty frame modeled though taking aerated concrete wall only as weight, AWF: the frame with aerated concrete wall. Normal floor weight (N), roof-floor weight (R) and total building weight at an incidence of earthquake (W) are provided in Table VII.

TABLE VII. BUILDING FLOOR WEIGHTS

Floor	$w_i (t)$			
	BEF	**BWF**	**AEF**	**AWF**
N	287.25	287.25	252.85	252.85
R	228.19	228.19	217.22	217.22
W	2813.44	2813.44	2492.87	2492.87

Building total weight was reduced by 11.36% with the use of aerated concrete wall instead of brick wall. The first natural vibration period of 10-story building along the y-axis was calculated with the aid of Rayleigh ratio. Period values are provided in Table VIII.

TABLE VIII. PERIOD VALUES OF THE BUILDING

Period (s)			
BEF	**BWF**	**AEF**	**AWF**
1.38	1.17	1.28	1.01

Period values decreased by 7.25% with decrease in building weight. Weight and modulus of elasticity together decreased period values by 13.68%. Period values decreased by 15.22% with the modeling of brick wall and 21.09% with the modeling of aerated concrete wall (Table IX). Total equivalent seismic load of 10-story building along the y-axis (base shear force) (V_t) was calculated and provided in Table X. Base shear force values decreased by 6.91% with decrease in building weight. Weight and modulus of elasticity together reduced base shear force values by 7.35%. Base shear force values increased by 13.70% with the modeling of brick wall and by 13.155 with the modeling of aerated concrete wall (Tables X-XI).

TABLE IX. % EDUCTIONS IN BUILDING PERIOD VALUES

BWF/BEF	**AWF/AEF**	**AEF/BEF**	**AWF/BWF**
15.22	21.09	7.25	13.68

TABLE X. BASE SHEAR FORCE VALUES

BEF	**BWF**	**AEF**	**AWF**
183.00	208.07	170.36	192.77

TABLE XI. % CHANGES IN BUILDING BASE SHEAR FORCE

BWF/BEF	**AWF/AEF**	**AEF/BEF**	**AWF/BWF**
(+)13.70	(+)13.15	6.91	7.35

Equivalent seismic loads were affected on the displaced center of gravity considering +5% additional eccentricity at floor alignments (e_y=0.5). Eccentricity-induced displacement values for the 10th floor of the building are provided in Table XII. Reductions in displacement values were also calculated and are provided in Table XIII.

TABLE XII. DISPLACEMENT VALUES OF 10TH FLOOR

Frames	$(d_i)_{min}$ **(m)**	$(d_i)_{max}$ **(m)**
BEF	0.0410	0.0579
BWF	0.0343	0.0470
AEF	0.0382	0.0539
AWF	0.0235	0.0318

TABLE XIII. % REDUCTIONS IN BUILDING DISPLACEMENT VALUES

Floor	**BWF/BEF**		**AWF/AEF**		**AEF/BEF**		**AWF/BWF**	
	min.	**max.**	**min.**	**max.**	**min.**	**max.**	**min.**	**max.**
10	16.37	18.80	38.49	41.07	6.87	6.88	31.50	32.42
9	16.75	19.06	39.03	41.46	6.87	6.88	31.79	32.65
8	17.07	19.24	39.51	41.88	6.89	6.90	32.09	32.99
7	17.32	19.35	39.95	41.96	6.86	6.89	32.36	32.99
6	17.58	19.42	40.29	42.11	6.90	6.90	32.55	33.12
5	17.72	19.37	40.60	42.16	6.88	6.91	32.78	33.21
4	17.71	19.17	40.77	42.05	6.92	6.90	32.99	33.26
3	17.50	18.67	40.63	41.65	6.96	6.87	33.04	33.19
2	16.57	17.50	39.93	40.52	6.90	6.90	32.97	32.88
1	13.73	14.23	36.94	37.03	6.72	6.82	31.82	31.59

Maximum displacement graphs of the 10-story building for different column sizes were drawn for all floors. Displacements increased with increasing number of floors (Figure 4).

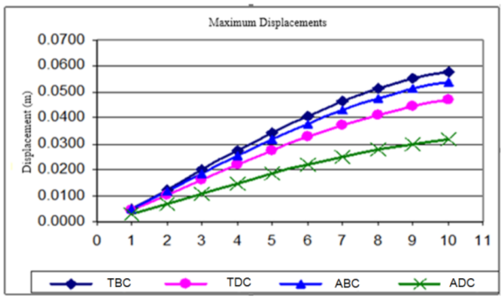

Fig. 4. Maximum deflection graphs of the building

Earthquake analysis for all frame systems of the building revealed that torsion irregularity, rigidity irregularity, relative floor displacement and second-order indicator values were below the limit values specified in [23].

IV. CONCLUSION AND DISCUSSION

In previous experimental studies, brick wall modulus of elasticity values were reported between 1000MPa–4272MPa and the taken value of 1000MPa, based on concrete class for hallow bricks used in construction of a hotel, was found to be suitable [14]. With the use of aerated concrete instead of brick in infill walls, the building's total weight decreased by 11.36%, period values decreased by 7.25%, base shear force values decreased by 6.91% and displacements decreased by 6.72%-6.96%. Weight and modulus of elasticity together reduced period values by 13.68%, shear force values by 7.35% and displacements by between 31.50%-33.26%. With the model of brick wall, period values decreased by 15.22%, shear force values increased by 13.70% and displacements decreased by between 13.73-19.42%. With the modeling of aerated concrete, period values decreased by 21.09%, shear force values increased by 13.15% and displacements decreased by between 36.94%-42.16%. Eventually, in Turkey where frequent earthquakes and heavy destructions are experienced, no concessions should be made on the quality and rigidity of the buildings. Therefore, the behavior of any single constructional member should be well-known and calculations should be made accordingly. Previous studies and present analysis reveal that infill walls have great contributions to building behavior under lateral loadings like earthquakes and negligence will bring about various negative outcomes. It is recommended that these existing structural members should definitely be included into calculations to improve positive impacts of infill walls on structure strength, elasticity and rigidity.

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