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Seismic Strengthening with Precast Panels - Theoretical Approach†

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ABSTRACT

An economical, structurally effective and practically applicable seismic retrofitting technique has been developed on the basis of the principle of strengthening the existing hollow brick infill walls by using high strength precast concrete panels. The technique would not require evacuation of the building and would be applicable without causing much disturbance to the occupant. For this purpose, eighteen one-bay two-story reinforced concrete frames with hollow brick infill walls were tested under reversed cyclic lateral loading simulating earthquake. The specimens were strengthened by using six different types of precast concrete panels. In the present study, hollow brick infill walls strengthened by using high strength precast concrete panels were modeled once by means of equivalent diagonal struts and once as monolithic walls having an equivalent thickness. The experimental results were compared with the analytical results of the two approaches mentioned.

Keywords: *Hollow brick infill wall, high strength precast concrete panel, seismic retrofitting, reinforced concrete frame with hollow brick infill walls, reversed cyclic lateral loading, equivalent diagonal strut, monolithic wall.*

1. INTRODUCTION

Many reinforced concrete (RC) framed buildings in Turkey don't have enough lateral rigidity against a possible earthquake. Therefore, a huge building stock awaits seismic retrofitting. Using cast in place RC infill walls is a widely used and reliable method in improving the overall system performance. By this technique, the building gains considerable strength and lateral rigidity. Many buildings in Turkey were repaired and strengthened with this method, especially after severe earthquakes. However, there are some drawbacks of this strengthening technique. The application of this method requires heavy construction work, so evacuation of the building becomes a necessity. Therefore, a very challenging aspect of the problem is how to introduce an economical, structurally effective and practically applicable pre-quake strengthening intervention without

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evacuating the building, even without causing more disturbances to the occupants than a simple wall painting operation. With the experimental studies conducted, an innovative occupant friendly retrofitting technique, suitable for the reinforced concrete framed structures with hollow brick masonry infill, has been developed. The idea is to convert the existing nonstructural hollow brick infill wall into a load carrying system acting as a cast-in-place concrete shear wall by bonding relatively thin high strength precast concrete panels to the plastered hollow brick infills by epoxy mortar. A single panel would be unmanageable, too large to go through doors and too heavy to be carried by two workers. Therefore, the panels to be bonded have to be of manageable size and weight, and have to be assembled on the infill side by side with the other panels.

The experimental studies conducted in the Structural Mechanics Laboratory of METU [1,2,3,4] have shown that the proposed method can safely and successively be used in the strengthening of the available building stock. Modeling of hollow brick infill walls strengthened by precast concrete panels in the structural analyses is an important topic. Two different analytical modeling methods are proposed in this study. In the first method, panel strengthened hollow brick infill walls are modeled as compression struts placed diagonally in the bays of a frame. The equivalent compression struts are supposed to be fixed to the frame by hinges at both ends. In the second method, aforementioned infills are modeled as monolithic shear walls (equivalent column method) having an equivalent thickness.

Analytical and experimental studies on infilled frames are being carried on for nearly fifty years. Determination of lateral load carrying capacity of an infilled frame is a complex process. First study on infilled frames was conducted by Polyakov [5] in the year 1950s. In 60s, Smith [6,7,8,9] and Carter[10], in 70s Mainstone and Weeks [11], Mainstone [12], Klingner and Bertero [13], in 90s Paulay and Prestley [14], Angel [15] and Al-Chaar [16] conducted analytical and experimental studies about the infill walls and contribute to better understanding of the infilled frame behavior.

2. EXPERIMENTAL STUDIES

2.1. Test Frames

In the experimental part of the study, one-third scale, one-bay, one or two-story R/C frames [1,2,3] with hollow brick infill walls were used as test units. Test frames were intentionally designed and constructed to have the most common deficiencies observed in residential buildings in Turkey. Such aforementioned deficiencies can be listed as low-grade concrete, use of plain reinforcement, insufficient lap splice length, insufficient confinement, strong beam-weak column connections and poor workmanship. All frames were infilled with scaled (one-third scale) hollow bricks covered with scaled layer of plaster at both faces. As in real practice, ordinary workmanship was employed while infilling the frames with hollow bricks and covering with plaster.

2.2. Precast Concrete Panels

Within the aim of this study, six different panel types were designed and used as hollow brick strengthening agencies. Similar to test frames, precast panels were also scaled down by 1/3 ratio. The major factor considered in the design of precast panels was weight. Taking into account the frame dimensions and the fact that each peace of panel to be used in the actual practice should not exceed 80 kg, high strength concrete panels were designed to have two main geometrical shapes. Considering the panel connection to be the weakest link of the chain, both shear keys and welded connections were used in the first two types. However, the epoxy mortar used in the panel joints behaved so successfully that both shear keys and welded connections were omitted to simplify the application in the latter panel designs.

For the aim of reflecting the actual practice, hollow brick infills, which had smaller thickness than the frame width, were placed eccentrically on the exterior side of the frame resulting with an even surface on one side of the frame and an indented one on the other. Both faces of the hollow brick infill wall were plastered. Interior panels were bonded to the indented face of the plastered hollow brick infill wall such that they were surrounded all around by frame members. This type of panel application is named as “Interior” in Table 1. To observe the possible difference in behavior, “Exterior” type of panels were bonded to the even face of the plastered hollow brick infill wall. This type of panel application is named as “Exterior” in Table 1. Panel types are shown in Figure 1. Panel Types A, B, C, and D show “Interior”, Types E and F show “Exterior” type of application. The last column of Table 1 shows the number of anchoraged sides of the base story of a frame.

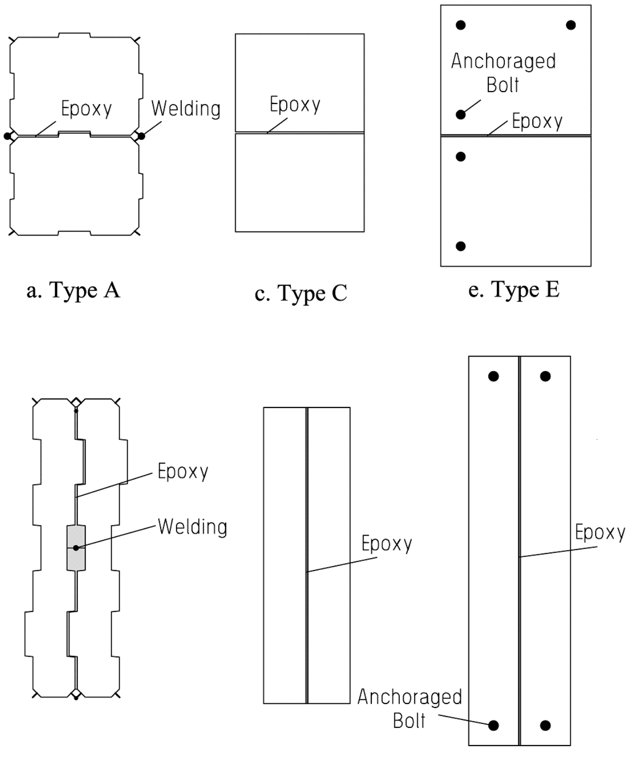
2.3. Material Properties

Test frames were intentionally cast with low strength concrete to reflect the common actual practice in Turkey. However, panels were cast with high strength concrete to minimize the thickness. Hollow brick infills, shown in Figure 2, were covered with ordinary cement-lime mixture plaster. Plain bars were used in the test frames.

Epoxy mortar SIKADUR 31 was used in bonding the panels to the plastered hollow brick infills, in between the panels and between the panels and the frame members.

2.4. Test Set-up

Rigid foundation beam of each test frame was bolted down to the RC universal base which serves as a rigid foundation for the frames and was fixed to the strong testing floor of the laboratory. Constant vertical load of 60 kN or 120 kN, around 10 or 20% of the column axial load capacity, was applied on columns by the help of two prestressing cables pulled down by two hydraulic jacks on either side of the frame. The axial load was continuously monitored and endeavored to be kept at the same level during the tests. Reversed cyclic lateral loading resembling earthquake effect was applied by using a double acting hydraulic jack bearing against the reaction wall. For two story test frames, lateral loading was applied on a spreader beam at one-third of its span to ensure that the lateral load at the second story beam level always remains twice as the lateral load at the first story beam level. For one story test frames, lateral loading was applied at the first story beam level. Test set-up is shown in Figure 3. Test results are summarized in Table 2.



a. Type A c. Type C e. Type E

b. Type B d. Type D f. Type F

Figure 1- Panel Types

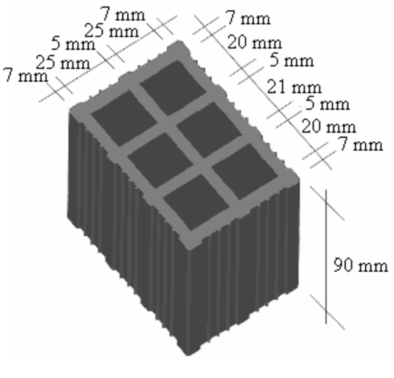


Figure 2 – Hollow Brick Infills used in the tests

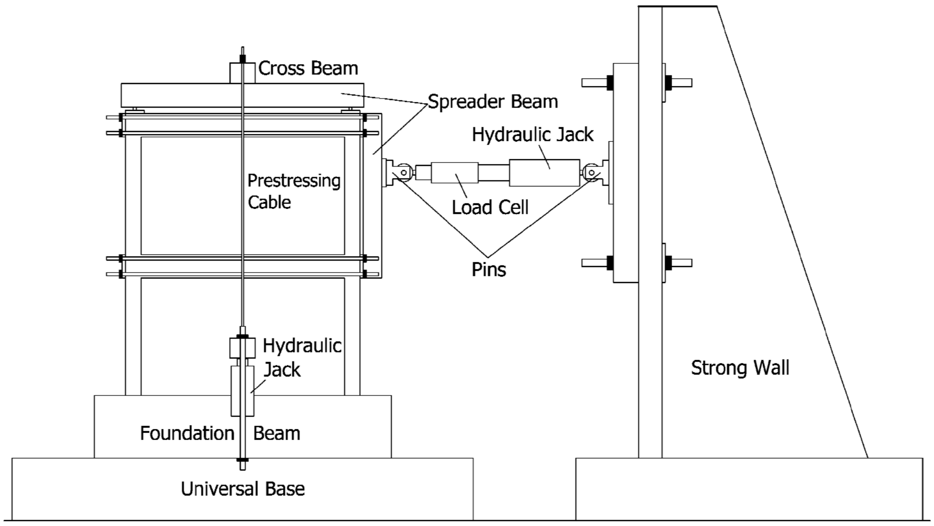


Figure 3 – Test set-up

3. ANALYTICAL STUDIES

3.1. Modeling the Panel Strengthened Hollow Brick Infill Wall as Equivalent Diagonal Strut

First study on infill walls was conducted by Polyakov [5] in the year 1950s. During these studies, diagonal cracks were observed in the center of the infill, separation was observed between the infill and the frame in the unloaded corners and full contact between the infill and the frame in the loaded corners. In the year sixties, Smith [6,7,8,9] and Carter[10] developed a design based on masonry modeled as compression strut. Results of this analytical study showed similarities with that of a later experimental study conducted by Mainstone [12] and Al-Chaar [16].

In the studies conducted in the Middle East Technical University Structural Mechanics Laboratory, Altın [17, 18] and Sonuvar [19] modeled RC infill walls as compression struts. However, modeling of panel strengthened hollow brick infill can neither be as that of masonry nor as that of RC infill wall. The combination of masonry and precast concrete panels is even more complicated to model.

To verify the experimental results obtained from the tests analytically, push-over analyses were performed. Push-Over analysis is a kind of nonlinear static analysis procedure that is generally used to evaluate the performance of the structures under lateral loads. In this analysis, a lateral displacement pattern is selected and applied to the structure in incremental steps. The procedure is illustrated simply in Figure 4. For the push-over analysis of the test specimens, inelastic plane frame computer program DRAIN-2Dx [20] was used. Using this computer program, analyses can be performed by either force controlled or displacement controlled procedures.

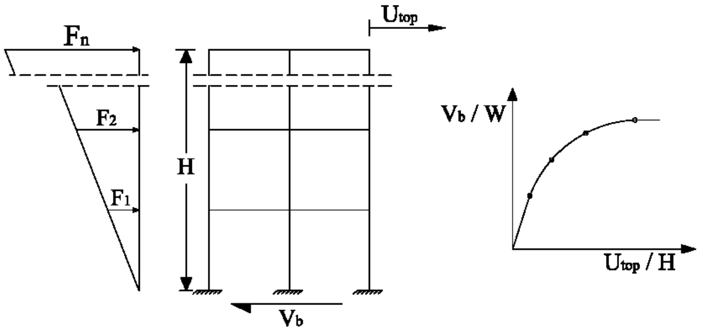


Figure 4 – Push-Over Analysis

3.1.1. Equivalent Compression Strut Modeling

Hollow brick infill walls strengthened by relatively high strength precast concrete panels were replaced with two equivalent diagonal compressive struts. One of the struts, each placed diagonally and fixed to frame by hinges at both ends, is to model the plastered hollow brick infill wall and the other is to model the whole panel made up of smaller carriable precast concrete panels. In both modeling, it is assumed that the infill is not connected to the frame. When the load is applied, separation occurred between the infill and the frame over a finite length of the beam and the column in the unloaded corners and full contact between the infill and the frame in the loaded corners. At this stage, a line drawn from one loaded corner to the other represents the direction of the principal compression. Therefore, infill transfers compression along this line (Figure 5). To determine the mechanical and geometrical properties of this virtual compression strut representing the infill, Equation 1 and Equation 2 is proposed by FEMA [21];

$$a_{\text{infill}} = 0.175\left(\lambda \cdot h_{col}\right)^{-0.4} d \tag{1}$$

$$\lambda = \sqrt[4]{\frac{E_{\text{infill}} b_w \sin(2\beta_s)}{4 E I h}} \tag{2}$$

In the equations, a_{infill} is the effective width of the equivalent compression strut, h_{col} is the height of the column measured between the beam-column joints, d is the diagonal length of the infill wall, E_{infill} is the modulus of elasticity of the infill, b_w is the thickness of the infill, β_s is the angle which has a tangent of infill height to length, E is the modulus of elasticity of the column, I is moment of inertia of the column, h is the height of the infill. The thickness of the equivalent compression strut should be the same as the thickness of the infill it models. Modulus of elasticity of the RC frame was calculated by Equation 3 [22].

$$E_c = 4750\sqrt{f_c} \quad \text{(MPa)} \tag{3}$$

Table 1 – Properties of the test frames

Number of Stories	Test Frame	Column Longitudinal Bar	N/N_0	Lap-Splice Length	Panel Application Face	Panel Type	Anchorage Side
Two Story	CR	Continuous	0.19	-	---	---	---
	LR	Lap-Splice	0.30	20 ϕ (1)	---	---	---
	CIA	Continuous	0.17	-	Interior	A	4
	CIB	Continuous	0.21	-	Interior	B	4
	CIC1	Continuous	0.19	-	Interior	C	1
	CID1	Continuous	0.19	-	Interior	D	1
	CIC3	Continuous	0.18	-	Interior	C	3
	CIC4	Continuous	0.17	-	Interior	C	4
	CEE4	Continuous	0.18	-	Exterior	E	4
	CEF4	Continuous	0.21	-	Exterior	F	4
	CEE1	Continuous	0.15	-	Exterior	E	1
	CEER	Continuous	0.20	-	Exterior	E	4 (reduced)
	LIC1	Lap-Splice	0.17	20 ϕ (1)	Interior	C	1
	LID1	Lap-Splice	0.22	20 ϕ (1)	Interior	C	1
One Story	1CR	Continuous	0.25	-	---	-	-
	1LR	Lap-Splice	0.13	20 ϕ (2)	---	-	-
	1CIA	Continuous	0.25	-	Interior	A	4
	1CIB	Continuous	0.25	-	Interior	B	4
	1CIC4	Continuous	0.25	-	Interior	C	4
	1CID4	Continuous	0.25	-	Interior	D	4
	1LIC4	Lap-Splice	0.13	20 ϕ (2)	Interior	C	4
	1LID4	Lap-Splice	0.13	20 ϕ (2)	Interior	D	4

(1) *20ϕ = 160 mm (lap-splice length on column longitudinal bar at both stories)*
(2) *20ϕ = 160 mm (lap-splice length on column longitudinal bar)*

Table 2 – Summary of test results

Number of Stories	Test Frame	Lateral Capacity (kN)	Remarks on Performance
Two Story	CR	78.8	Typical infilled frame behavior
	LR	74.2	Typical infilled frame behavior
	CIA	192.5	Wall behavior, intact panel
	CIB	201.3	Wall behavior, intact panel
	CIC1	195.7	Damage in panel & frame
	CID1	192.7	Damage in panel & frame
	CIC3	210.6	Damage in panel & frame
	CIC4	218.5	Wall behavior, intact panel
	CEE4	206.6	Smeared cracking, light damage
	CEF4	204.3	Smeared cracking, light damage
	CEE1	177.0	Separation, unsatisfactory performance
	CEER	185.4	Smeared cracking, light damage
	LIC1	174.0	Damage in panel & frame
	LID1	172.4	Damage in panel & frame
One Story	1CR	86.6	Typical infilled frame behavior
	1LR	65.5	Typical infilled frame behavior
	1CIA	209.9	Damage in panel & frame
	1CIB	197.0	Damage in panel & frame
	1CIC4	213.5	Damage in panel & frame
	1CID4	254.7	Damage in panel & frame
	1LIC4	148.9	Heavy damage in panel & frame
	1LID4	199.6	Heavy damage in panel & frame

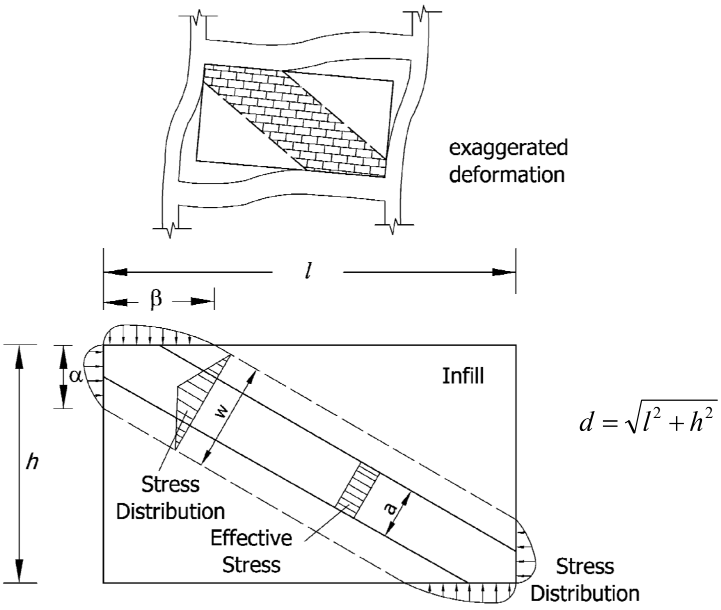


Figure 5 – Compression Region on the Infill Under Lateral Loading and Equivalent Diagonal Compression Strut Representing the Infill

Panel strengthened plastered hollow brick infills, modeled as diagonal compression struts, are represented by elastic-brittle bars in compression with no tensile resistance in the computer program. Therefore, equivalent axial stiffness and yielding resistance of diagonal strut modeling plastered hollow brick infill wall are to be calculated. In all test frames, specially produced and scaled (one-third scale) hollow brick infills were used as infill material. Details of the hollow bricks are illustrated in Figure 2. Four plastered hollow brick infill wall specimens having dimensions of 700 mm × 700 mm and by using same materials were produced in the Structural Mechanics Laboratory of METU. These specimens were tested under diagonal compression, as in the case of the plastered hollow brick infill walls of the test frames [23] and the mean compressive strength $f_{c,infill}$ was obtained as 5.0 MPa and the mean modulus of elasticity, E_{infill} as 7,500 MPa. Geometry of the plastered hollow brick infill walls of the test frames were rectangle with an aspect ratio of 1.733:1 (dimensions are 1300 mm × 750 mm). When the aspect ratio increases, an increase in the load capacity is expected resulting from the increase in the diagonal length and area in tension. This behavior was observed in the panel tests with different aspect ratios conducted by Marjani [24]. However, since the capacity ratio is less than 10%, rectangular infill wall specimens appeared to be adequate. The relatively high value of the modulus of elasticity obtained from the panel tests resulted from the scale of the hollow brick infills. Although the outer dimensions of the hollow brick infills were scaled down (one-third scale), it could not be possible to scale down the thicknesses of the inner walls. Varying values of $f_{c,infill}$ and E_{infill} are given in the literature for the different studies conducted. For example, in the experimental studies conducted by Istanbul Technical University, they were taken as

$f_{c,infill}$=2.0 MPa and E_{infill}=6,000 MPa, in the experimental studies conducted in Structural and Earthquake Laboratory of Selcuk University, they were taken as $f_{c,infill}$=1.85 MPa and E_{infill}=5,750 MPa and in the studies conducted by Paulay and Prestley as [14] $f_{c,infill}$=3.0 MPa and E_{infill}=8,250 MPa [25].

Using the experimental results, the strength of the equivalent compression strut used in the modeling can be calculated using Equation 4:

$$F_{\mathrm{c,infill}} = f_{\mathrm{c,infill}} \cdot a_{\mathrm{infill}} \cdot b_w \tag{4}$$

The thickness and the modulus of elasticity of the equivalent strut should be the same as the thickness of the infill it models. The rigidity of the strut can be calculated using FEMA [26]:

$$k_{\mathrm{infill}} = \frac{b_w \cdot a_{\mathrm{infill}} \cdot E_{\mathrm{infill}}}{d} \tag{5}$$

Using Equation 4 and Equation 5, the strength and initial rigidity of the strut modeling the plastered hollow brick infill wall was calculated as 70 kN and 70kN/mm, respectively. Then, the load-deformation curve necessary for the computer program is prepared as in Figure 6.

Up to this point, the modeling of the first equivalent diagonal compression strut is shown. The second strut will model the strengthening panels. Since the whole panel made up of smaller carriable panels can be accepted to be of a homogeneous and isotropic material, the geometrical properties of the second strut will be resolved using a method proposed by Smith and Carter [6-10]. According to Smith and Carter, the relative stiffness of the infill to the column can be represented by a non-dimensional parameter, λh. Equation 2 can be used to calculate λ. The length of contact between the column and the infill has been derived using “free beam on an elastic foundation, subjected to a concentrated load” analogy and can be presented by Equation 6;

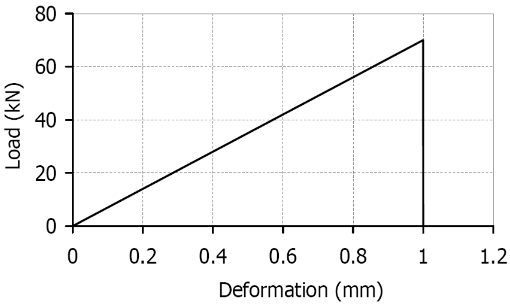


Figure 6 - Idealized Force-Deformation Diagram of Elasto-Plastic Bar to Model the Plastered Hollow Brick Infill Wall

$$\frac{\alpha}{h} = \frac{\pi}{2\lambda h} \qquad \text{(here, } \alpha \leq h/2 \text{)} \tag{6}$$

where h is the height of the column between center-lines of beams. Smith and Carter assumed that the infill has no rotation, a triangular stress distribution exits along the contact length of the column and the infill, the infill is not bonded to the frame and also β was equal to half length of the infill.

Theoretical values of infill's rigidity can be calculated from the assumption of stress distribution affecting the infill's sides. For different aspect ratios, *l/h*, and different contact ratios, *a/h*, theoretically calculated values for w_{panel}/d ratio are given in Table 3 [6]. In this table, *d* is the diagonal length of the infill and w_{panel} is the width of the equivalent strut. The values in Table 3 are given for a homogeneous and isotropic material.

Moduli of elasticity of the panels can be calculated using Equation 3.

Table 3 – Theoretical values of "w_{panel}/d" ratio

Interaction Distribution		Panel aspect ratio (*l*/*h*)			
α/*h*	β/*l*	1:1	1.5:1	2.0:1	2.5:1
1/8	½	0.24	0.22	0.18	0.16
1/4	½	0.30	0.27	0.23	0.18
3/8	½	0.35	0.32	0.26	0.22
1/2	½	0.38	0.38	0.30	0.25

The program used accepts axial load-moment interaction curve as yield/rupture surface or moment capacity value independent from axial load as yield criteria for frame members. In this study, interaction curves for the column members and moment capacity values (elasto-plastic) for the beam members are used in the program. For the specimens with lap-splices in column longitudinal bars, the yield stress can not be reached due to inadequate lap-splice length. Yield stress of column longitudinal bars with inadequate lap-splice length (20ϕ) is calculated by using Equation 7 [27]:

$$f_y' \cong f_y \sqrt{\frac{20\phi}{40\phi}} = 0.7071 f_y \tag{7}$$

Load carrying capacity of the strut modeling the whole panel made up of smaller carriable panels can be calculated using Equation 8:

$$F_{c,panel} = \gamma \cdot f_{c,panel} \cdot b_w \cdot w_{panel} \tag{8}$$

where $F_{c,\,panel}$ is the axial load carrying capacity of the equivalent compression strut, γ is a constant dependent on the concrete compressive strength of the precast panels, $f_{c,panel}$ is the concrete compressive strength of precast panels, b_w is the thickness of the imaginary equivalent diagonal strut (20mm), w_{panel} is the width of the equivalent strut, which will be calculated by using the w_{panel}/d values given in Table 3 (proposed by Smith [6]).

Non-linear push-over analysis (displacement controlled) of the test frames were performed for different values of γ. The mean value and the standard deviation of the γ values for which the analytical and experimental envelope curves of all the test frames best fit each other are calculated as 0.45 and 0.087, respectively. In a different study [28] conducted in the Structural Mechanics Laboratory of METU and using the same test set-up, RC test frames were strengthened by pouring shotcrete on to the hollow brick infills. In this study, it was observed that when concrete compressive strength of shotcrete increased 60%, lateral load carrying capacity of the strengthened frame increased by 23%. Best fit γ values for all the test frames and concrete compressive strength of precast panels ($f_{c,panel}$) are given in Figure 7. The equation of an approximate trend line for all of the points on this graph is given as in Equation 9:

$$\gamma = 7\left(f_{c,panel}\right)^{-0.75} \tag{9}$$

Then, the axial load carrying capacity of the equivalent compression strut modeling the precast concrete panels can be calculated as in Equation 10,

$$F_{c,panel} = 7 \cdot \left(f_{c,panel}\right)^{0.25} \cdot b_w \cdot w \tag{10}$$

In summary, as two equivalent compression struts are used in the analytical modeling of the strengthened frames, Equation 11 can be written,

$$F_{strut} = F_{c,\text{infill}} + F_{c,panel} \tag{11}$$

3.1.2. Push-Over Analysis of the Test Frames Modeled with Equivalent Compression Struts

Following the above-mentioned steps, an analytical model was prepared for the strengthened test frames as presented in Figure 8. In the model, hollow brick infill walls strengthened by relatively high strength precast concrete panels were replaced with two equivalent diagonal compressive struts. One of the struts is to model the plastered hollow brick infill wall and the other to model the whole panel made up of smaller carriable precast concrete panels.

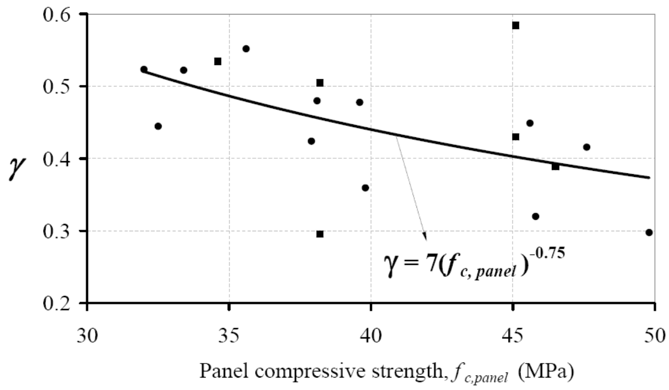


Figure 7 - Panel compressive strength - γ values

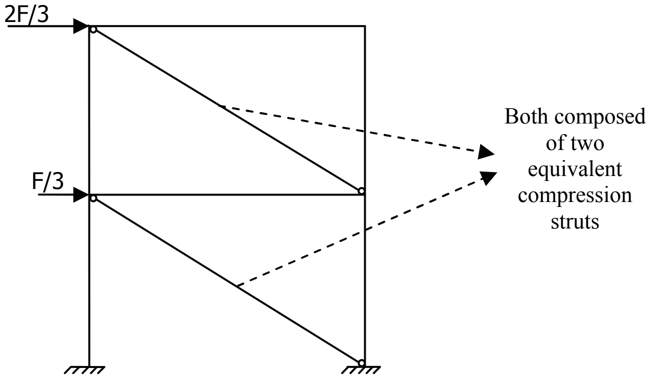


Figure 8 - Analytical modeling of the strengthened test frames

Load – deformation curves obtained by equivalent diagonal compression strut method are presented in Figure 11. On these graphs, curves obtained by equivalent column method, explained in the next section, are also given.

3.2. Equivalent Column Method

Equivalent column method is an alternative method besides the equivalent diagonal compression method. The strengthened infill wall is modeled as equivalent column. Since the equivalent column model of such structural members is widely used by the designers, it might be beneficial to compare the results of both proposed analytical methods. The description of the equivalent column method is simply illustrated in Figure 9. In the model, whole frame with strengthened infill walls is defined as a single column. To form the interaction curves of each strengthened test frame, an equivalent thickness has to be taken into account instead of the thickness of the whole panel strengthened hollow brick infill wall. For the equivalent thickness calculation, Young's Modulus of each layer is used. In the analyses, mesh steel used for panel reinforcement is also taken into account.

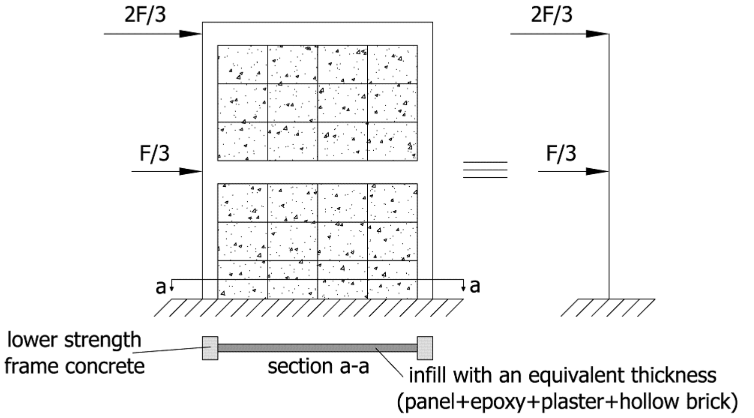


Figure 9 – Equivalent column model of the strengthened test frames

Calculation of the equivalent thickness of the panel strengthened plastered hollow brick infill is simply shown in Figure 10. In the calculations, modulus of elasticity of the plastered hollow brick infill was taken as 7,500 MPa, modulus of the elasticities of the frame and panel concrete were calculated according to the Equation 3. Data for equivalent thickness calculation to be used while forming the interaction diagrams of the equivalent columns is tabulated in Table 4.

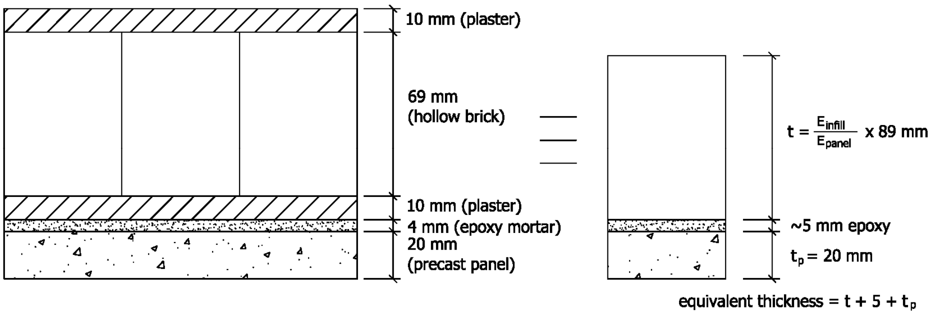


Figure 10 – Calculation of the equivalent thickness

It should be noted here that, according to the test results, exterior type of panels (Type E, Type F) behaved effectively as much as that of interior type of panels (Type A, Type B, Type C, Type D) when properly connected to the frame members with bolts. In the equivalent column analysis, it was decided to take the precast concrete panel thickness as 10 mm for the test frame CEE1, only. This was due to the fact that panels of this specimen were bonded to the plastered infill wall only by means of epoxy mortar, no ϕ8 mm bolts were used. In case of interior type panels and exterior type panels when connected to the frame members with ϕ8 mm bolts, actual thickness of the panels, 20 mm, were taken into account.

Table 4 – Data for equivalent thickness calculation

Specimen Designation	f_c	$f_{c,panel}$	E_c (MPa)	E_c (MPa) (reduced)	E_{panel} (MPa)	E_{infill} (MPa)	Equivalent thickness (mm)
CIA	18.2	32.5	20,000	14,000	27,000	7,500	50
CIB	13.0	38.1	17,000	12,000	29,300	7,500	50
CIC1	15.6	33.4	18,750	13,000	27,500	7,500	50
CID1	16.2	32.0	19,000	13,500	27,000	7,500	52
CIC3	17.3	47.6	20,000	14,000	32,800	7,500	48
CIC4	19.4	45.6	21,000	14,500	32,000	7,500	48
CEE4	18.1	39.6	20,000	14,000	29,900	7,500	50
CEF4	14.3	35.6	18,000	12,500	28,500	7,500	50
CEE1	22.2	45.8	22,500	15,500	32,150	7,500	35
CEER	15.1	37.9	18,500	13,000	29,250	7,500	49
LIC1	19.3	39.8	21,000	14,500	30,000	7,500	50
LID1	13.5	49.8	17,400	12,000	33,500	7,500	48
1CIA	18.7	34.6	20,500	14,500	28,000	7,500	45
1CIB	12.2	46.5	16,500	11,500	32,500	7,500	45
1CIC4	14.2	38.2	18,000	12,500	29,500	7,500	45
1CID4	11.1	45.1	16,000	11,000	32,000	7,500	45
1LIC4	15.7	38.2	19,000	13,500	29,500	7,500	45
1LID4	10.1	45.1	15,000	10,500	32,000	7,500	45

The Young's Modulus of all test frames was decreased intentionally by 30%, in order to enable cracks to be observed in the early cycles. In addition, reduced yield stresses for test frames with lap-splices in column longitudinal bars were calculated by Equation 7. Load-deformation curves obtained by equivalent compression strut and equivalent column methods together with the response envelope curves of two-story and one-story test frames are compared in Figure 11 and Figure 12, respectively.

According to the curves shown in Figure 11 and Figure 12, lateral load carrying capacities and initial rigidities of the test frames can adequately be calculated with acceptable accuracy. For two-story specimens, the deviation in the estimation of the lateral load carrying capacities of the test frames is 16.2% above and 7.2% below the experimental values with the equivalent compression strut method. These values are 1.9% above and

12.4% below the experimental ones with the equivalent column method. For one-story test specimens, the deviation in the estimation of the lateral load carrying capacities is 29.3% above and 22.3% below the experimental ones. These values are 24.1% above and 7.0% below the experimental ones with the equivalent column method. Test results of one-story test frames show that Type D panels behave more effectively than Type C panels. In the application of Type D panels, number of anchorage bars fixed to the frame elements is greater and a more efficient load transfer between the frame and the panel strengthened infill wall can be achieved. Although the equivalent column method represents the lateral load carrying capacities of the test frames as successfully as the equivalent strut method, it overestimates the initial rigidities of the test frames in spite of decreased Young's Modulus values. In addition, equivalent column method does not satisfactorily simulate the post-peak portion (descending portion) of the push-over curves, as expected. In this method, plastered hollow brick infills together with the precast concrete panels are modeled as one-dimensional members (cantilever column) whereas beams of the RC frame are not taken into account.

4. RESULT

This study examines how high strength precast concrete panel strengthened hollow brick infills can be modeled through computer software. Here, the aim is to develop a simple model that can safely be used by engineers. Since elastic analysis procedures are generally used, calculation of lateral load carrying capacity with certain precision is aimed instead of modeling of all the behavior.

Two approaches are proposed for modeling. In the first approach, strengthened infill walls are modeled by two different diagonal compression struts. First strut models the existing plastered hollow brick infills whereas the second strut models the high strength precast concrete panel wall. In the second approach, strengthened hollow brick infill and its side columns are modeled as a single column. In this approach, panel bonded hollow brick infill is converted into a wall with an equivalent thickness.

With the panel connection details used in the tests and within the panel compressive strength limits, acceptable results were obtained from push-over analyses. Following conclusions can be drawn according to the analysis conducted:

- Lateral load carrying capacity required for the design state can be calculated with adequate approximation by both proposed methods.
- Post-peak (descending portion) behavior of the push-over curves can not be simulated properly by both proposed methods.
- Both proposed methods can easily be adapted into the elastic modeling of RC framed structures. By this way, considerable amount of time and work might be saved.

However, these observations are limited only to the tests performed in this study. Generalization of both methods should be made carefully.

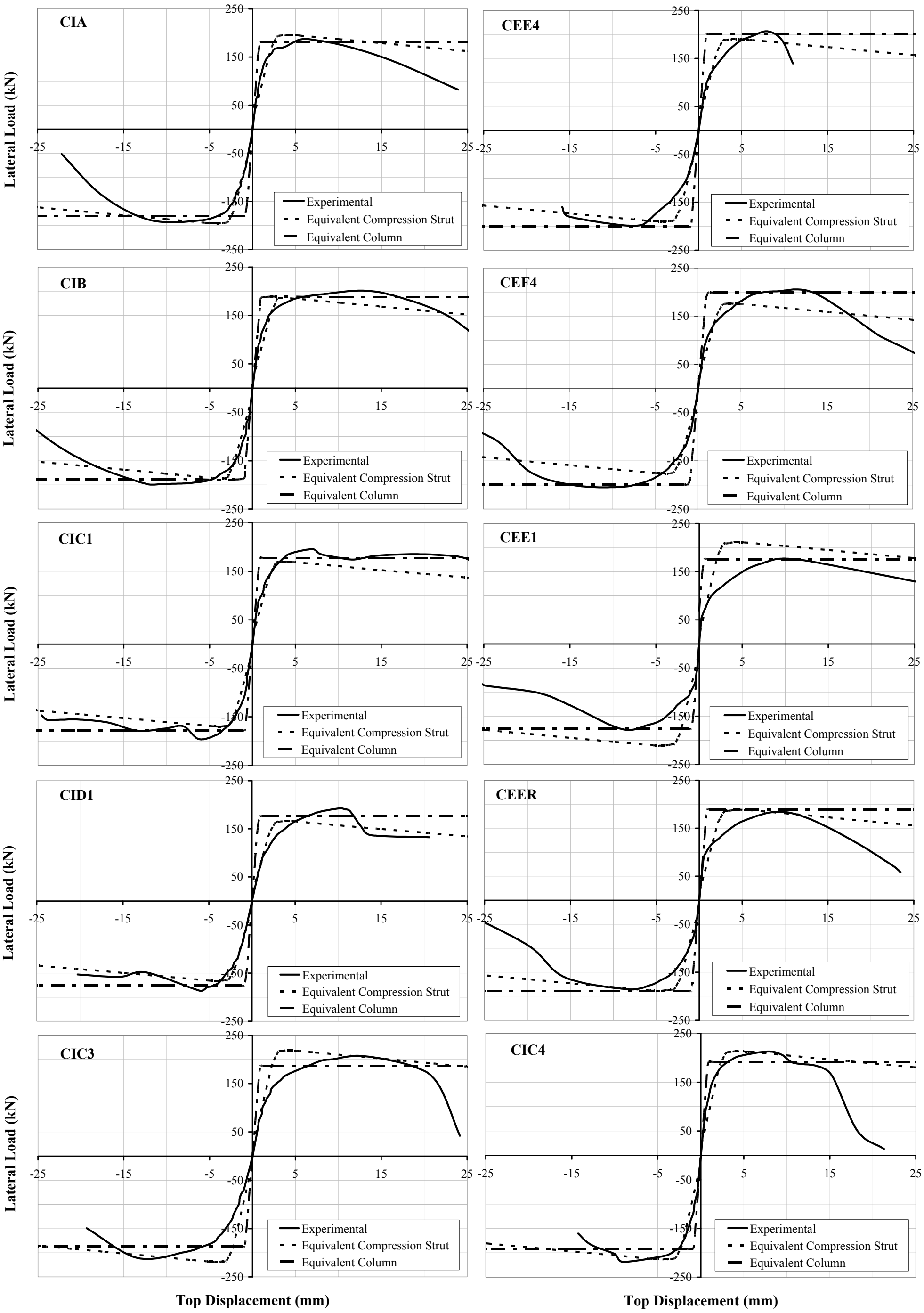


Figure 11 – Push-over analyses by equivalent strut and equivalent column methods (2 st.)

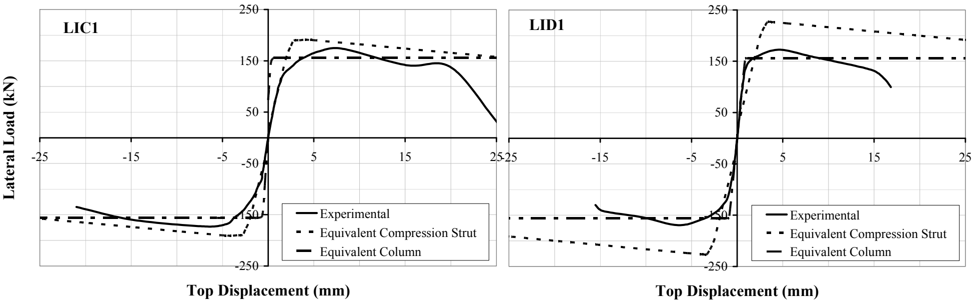


Figure 11 – Push-over analyses by equivalent strut and equivalent column methods (2 st.) Continued

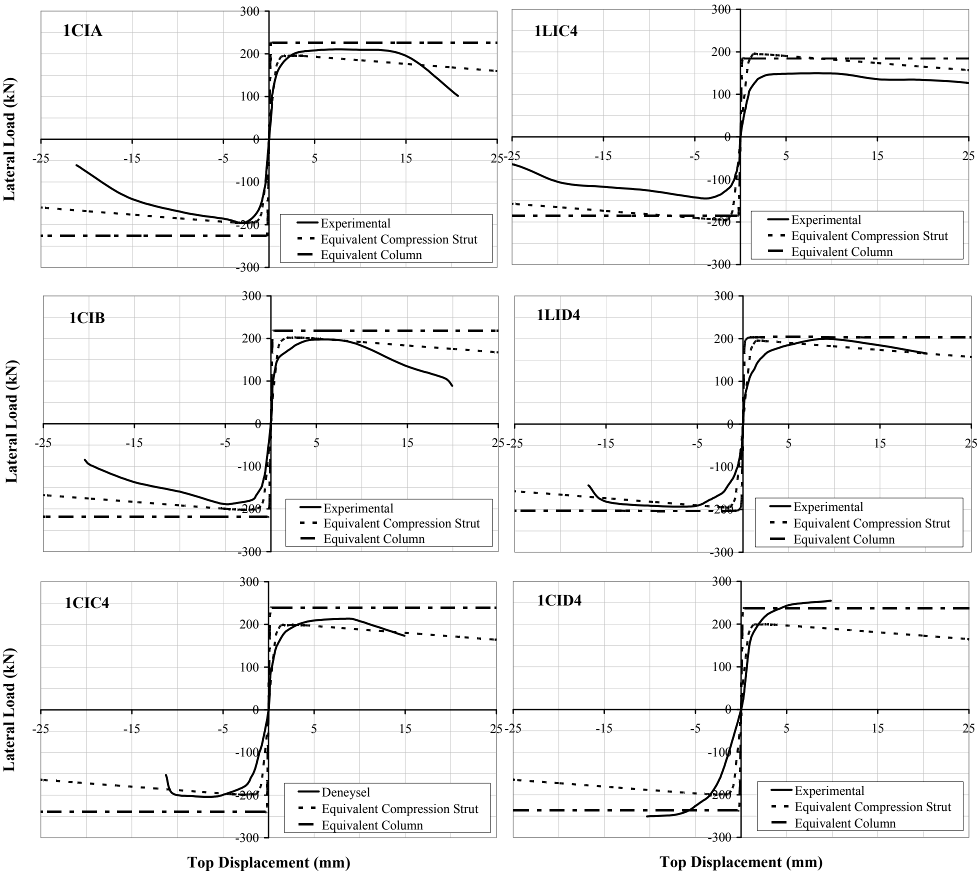


Figure 12 – Push-over analyses by equivalent strut and equivalent column methods (1 st.)

Symbols

a_{infill} : Effective width of equivalent compression strut modeling hollow brick infill

b_{w} : Infill thickness, equivalent compression strut thickness

d : Diagonal length of the infill

E : Young's Modulus of the column

E_c : Young' Modulus of the frame concrete

E_{panel} : Young's Modulus of the precast concrete panels

E_{infill} : Elasticity modulus of the infill

f_c : Compressive strength of the frame concrete

$f_{\mathrm{c,panel}}$: Compressive strength of the precast concrete panels

$f_{c,\mathrm{infill}}$: Compressive strength of the plastered hollow brick infill

f_y : Yield strength of the column longitudinal bar

f'_y : Reduced yield strength of the column longitudinal bar with lap-splice

F_{strut} : Axial load carrying capacity of the equivalent diagonal compression strut modeling the plastered hollow brick infill strengthened by panels

$\mathrm{F_{c,infill}}$: Axial load carrying capacity of the equivalent diagonal compression strut modeling the plastered hollow brick infill

$F_{c,\mathrm{panel}}$: Axial load carrying capacity of the equivalent diagonal compression strut modeling the whole panel made up of smaller panels

h : Height of the infill

h_{kol} : Column height between the centre-lines of the beams

k_d : Stiffness of the equivalent diagonal compression strut modeling the hollow brick infill

I : Moment of inertia of the column

l : Length of the infill

t : Equivalent thickness of the hollow brick infill wall strengthened by precast concrete panels (Equivalent column method)

t_p : Panel thickness

w_{panel} : Width of the equivalent diagonal compression strut modeling the panel

α : Interaction distribution ratio between the column and the infill

β : Interaction distribution ratio between the beam and the infill

β_s : Angle which has a tangent of infill height to length

ϕ : Diameter of the column longitudinal bar

λ : Characteristic of the infilled frame

γ : Coefficient

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