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A COMPLEMENTARY EXPERIMENTAL WORK ON BRITTLE PARTITIONING WALLS AND STRENGTHENING BY CARBON FIBERS

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SUMMARY

Diagonal tensile tests have been carried out on totally 28+37= 65, 755 mm x 755 mm square wall panels made of traditionally used low strength brittle bricks and recently produced high strength hollow block two holed bricks. Some of the wall panels are plastered and CFRP layers have been bonded on some of them with different application types, prior to tests. The results are presented in two groups of diagrams in terms of load-diagonal shortening and shear stress-shear angle. The nonlinear behavior of these brittle specimens has been obtained at the end, which can be utilized in nonlinear analysis. The results of six one story-one bay RC frames, infilled by the same materials used in shear panel tests, have been presented in the second part of the paper.

INTRODUCTION

One of the most promising ways of strengthening the existing low-rise reinforced concrete poorly designed and constructed nonductile buildings, is to modify their non-structural brittle partitioning walls to structural walls. In fact, it is known that the contribution of non-structural brittle walls on the overall structural behavior, especially at the beginning of the earthquake, is substantially high to be considered in response, until the shear transfer between the wall and peripheral elements drops to zero and out-of-plane inertia forces due to the other components of earthquake excitation overturns the freestanding walls, Yuksel [1], Mourtaja [2], Yuksel [3], Karadogan [4]. It has been observed in the field after the earthquakes and at the end of the experimental works in the laboratory that; even with the brittle brick partitioning walls that are very well integrated to the surrounding RC elements, it is possible to achieve considerable increase in the stiffness and the strength of the structure, Yuksel [5]. Several techniques that have been tested experimentally for the integration of walls to the frames and/or upgrading, are presented in this paper in the way of searching the most affordable and effective one. A short summary of the results obtained at the end of shear tests carried out for wall panels, which are unplastered, plastered and/or CFRP strengthened, will be presented to support the theoretical works needed for interpretation of the results of the six one story-one bay frames tested in laboratory.

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SPECIMENS

Two groups of specimens have been fabricated for a complementary research program launched in Structural and Earthquake Engineering Laboratory of Istanbul Technical University, I.T.U. In order to observe the effect of strengthening of the existing RC low-rise buildings with brittle infill walls by carbon fibers, a series of tests has been done in the laboratory and a part of this study will be presented here. The first group consists of the 65 wall panel specimens for shear tests. In the second group, there are six ½ scale, one story-one bay RC frames with infill walls.

First group of specimens:
755 mm by 755 mm square wall panels of the first group of specimens have been fabricated using different local material. Shear tests are carried out in two series. Low strength brittle bricks, which are widely used in partitioning walls in Turkey, are selected as the infill material for the first series of wall panels. The compressive strength in the direction of the holes of this type of brittle bricks is between 2.5-10 MPa. The void ratio of bricks is around 60%. The water:cement:lime:sand volumetric mixture proportions of mortar are 1:1:0.5:4.5 and mortar layer thickness is 10 mm.

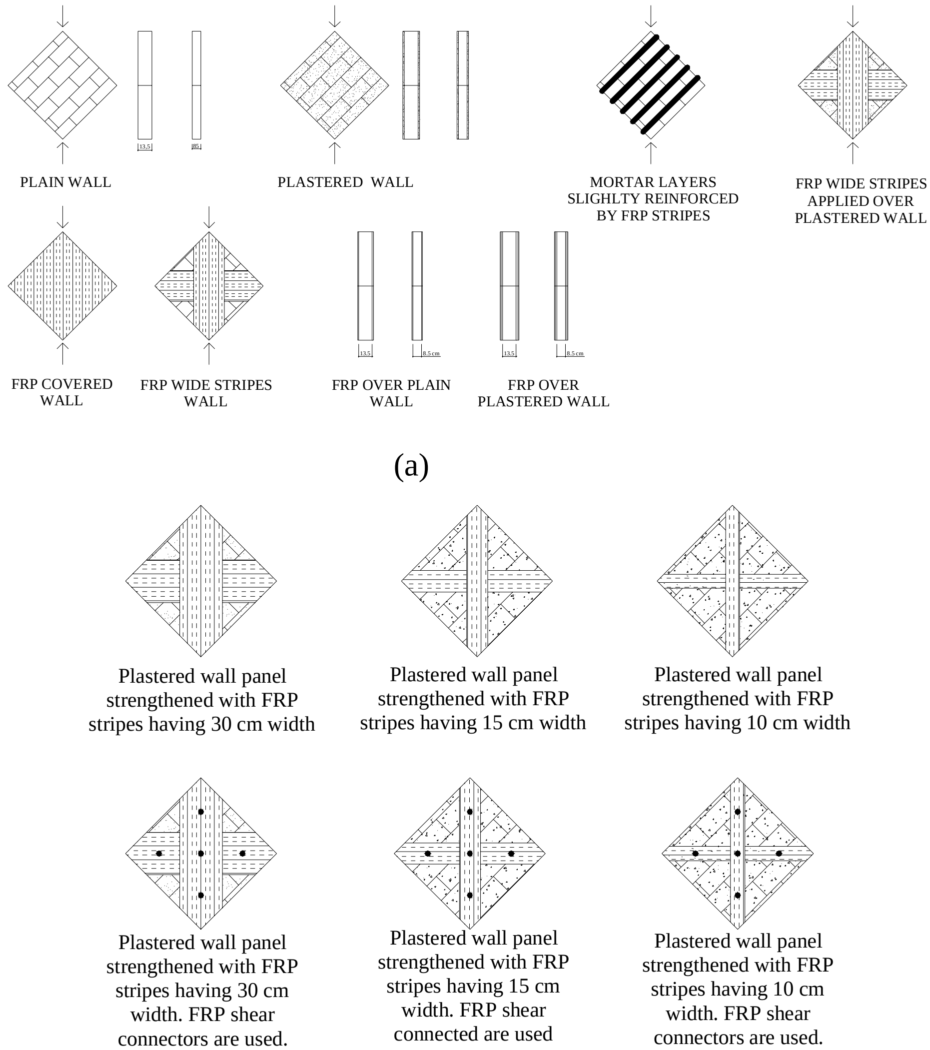
The first series of shear tests containing 28 wall panels, are divided into two sets. The first set includes 20 wall panel specimens, which are fabricated primarily. The following three parameters are chosen prior to the fabrication of these specimens. The thickness of the wall specimens is chosen as the first parameter. 135 mm and 85 mm are selected as the thicknesses of the brick walls. The rest of the dimensions of the two bricks are 200 mm. Considering the difficulty of removing the plaster from the existing wall surface, CFRP stripes are bonded over both plastered and non-plastered wall specimens. Therefore the second parameter is chosen as the existence of plaster layer on the wall surface. Water:cement:lime:sand volumetric mixture proportions of plaster are 1.25:1:0.5:4.5. The thickness of plaster is approximately 10 mm. Third parameter is the surface area of CFRP applied over the wall specimens. Two different types of applications of CFRP stripes are done. One of them is covering all the surface area of wall panel with CFRP and the other is strengthening the wall panel with 30 cm width CFRP stripes. CFRP stripes are applied diagonally on both sides of the wall panels and their fiber directions are in diagonal direction. Furthermore, CFRP stripes are embedded in the continuous mortar layers of some specimens at the fabrication stage.

Depending on the earlier results achieved through the evaluation of load-vertical displacement (P-Δ) curves and observed failure modes of the first set of specimens, a new set of 8 specimens have been fabricated. Embedding CFRP stripes in the mortar layers are not applied at this second set, as this kind of strengthening do not expose a significant effect on the ultimate load. Since the plastered specimens have a relatively higher ultimate loads and initial stiffness, all the specimens of second set are decided to be plastered.

At the pilot test of infilled frame, presented below, it is observed that main factor which controls the failure mode is the brittle behavior of the brick. The failure mode takes place by the separation of CFRP from the wall surface, after the shear strength of brick has been reached. For being able to benefit from CFRP until the failure, shear connectors bonding the CFRP layers on the both sides of the specimen are used at the second set wall panels.

Finally, the width of CFRP layers is chosen as the last parameter, for searching a cost effective solution. CFRP stripe widths of second set are 300 mm, 150 mm and 100 mm. Two wall specimens have been fabricated for each CFRP width and one with CFRP shear connectors while the other without any connector.

In order to place CFRP shear connectors, five holes are drilled on the wall panels. CFRP stripes are folded and put into these holes in a way that approximately 10 cm long ends of shear connectors are left outside the wall surface. Afterwards fibers of these ends are separated and bonded on the wall with adhesive. Each CFRP shear connector has the same width with CFRP stripes connected. All the types of first series of wall panels can be seen in Figure 1.



(b)

Figure 1a,b. First (a) and second (b) sets wall panels of low strength brick walls

The fabrication stage of second set of specimens and FRP shear connectors are shown in Figure 2.

Figure 2. Strengthening process of the second set of wall panels of first series

Three standard cylinder specimens are tested for each bench of mortar mix used in these shear test specimens. For tensile strength of mortar, additional three point bending tests are carried out as well.

All the other features of the first series of specimens are summarized in Table 1.

Table 1. Low strength brick wall panels

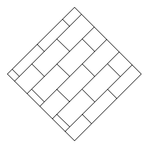
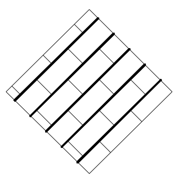
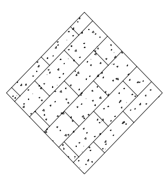
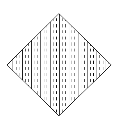
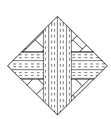
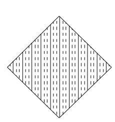
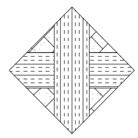
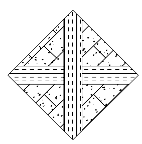
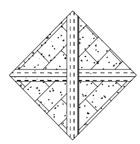
Specimen Name	Specimen Type		Thickness (cm)	Mortar Compressive Strength (MPa)	Plaster Compressive Strength (MPa)	Ultimate Load (kN)
S25	S-5		13.5	3.93	-	71
S4	S-1			6.94	-	-
S9	S-2			4.80	-	68
S16	S8-1		8.5	11.50	-	66
S18	S8-2			6.21	-	77
S11	SL-1		13.5	5.82	-	85
S12	SL-2			5.82	-	82
S13	SL-3			4.44	-	122
S14	SL8-1		8.5	4.44	-	73
S2	SS-1		13.5	5.75	8.22	134
S6	SS-2			6.55	7.27	244
S8	SS-3			7.16	8.22	207
S15	SS8-1		8.5	11.50	14.59	212
S17	SS8-2			11.50	14.59	207
S7	SW-1		13.5	7.16	-	221
S3	SW30-1			Curing errors.		
S20	SW30-2					
S19	SSW-1			9.28	14.59	384

Table 1. (Cont.) Low strength brick wall panels

Specimen Name	Specimen Type		Thickness (cm)	Mortar Compressive Strength (MPa)	Plaster Compressive Strength (MPa)	Ultimate Load (kN)
S1	SSW30-1			8.56	14.59	280
S5	SSW30-2			6.55	6.58	387
S10	SSW30-3			4.80	2.98	-
S21	SSW30A			5.18	3.23	94/211*
S28	SSW15			3.05	2.98	190
S24	SSW15A		13.5	3.93	3.23	162/197*
S27	SSW10			2.71	2.98	103
S26	SSW10A			2.71	2.98	142
S23	SSW30A			Error at the CFRP application stage.		
S22	SS-4			Spare specimen.		

Letters in the specimen type refers to:
1st S: Specimen, **2nd S**: Plastered specimen, **W**: CFRP stripes on all over the surface area, **W30/15/10**: CFRP stripes with 30/15/10 cm width, **8**: specimens having 8.5 cm thickness, **A: C**FRP shear connectors

The second series of shear test specimens are made of locally produced high strength hollow block bricks. Brick and mortar types and the amount of reinforcement are studied as three parameters of 37 wall panels. Three types of bricks having compressive strengths, in the direction of holes, varying 40 to 80 MPa are chosen. In order to investigate the effect of mortar compressive strengths on the shear strength of wall panels, three types of mortar are chosen. The two of them, M1, and M2 have volumetric mixture proportions cement:sand:water 1.5:4.5:1.5, and 1.5:4.5:1, respectively. BL07 is the specially produced mortar with very high compressive strengths. The volumetric mixture proportion of this mortar is special mortar:water 4:1. Certain amounts of vertical reinforcements, which are 0, 2, 4, and 6 reinforcements, are placed passing through the holes of bricks, and later on these holes are filled with mortar, (Figure 3).

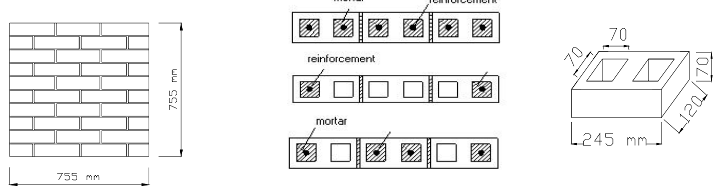


Figure 3. High strength brick walls

All the features of the second series of specimens are tabulated in Table 2.

Table 2. High strength brick wall panels.

Specimen Name	No of Reinforcing Bars	Mortar Type	Mortar Compressive Strength (MPa)	Brick Type	Brick Compressive Strength (MPa)	Reinforcement Yielding Strength (MPa)	Ultimate Load (kN)	τ_{max} (MPa)
S43	0	M1	2.42	A1	50.88	-	**121.9**	**0,951**
S47		M1		A1		-	**136.6**	**1,066**
S51		M1		G	87.88	-	**144.2**	**1,125**
S55		M1		A1	50.88	-	**145.1**	**1,132**
S59		M2	6.86	G	87.88	-	**157.1**	**1,226**
S63		M2		G		-	**148.9**	**1,162**
S67		BL07	38.58	G		-	**251.4**	**1,779**
S71		BL07		G		-	**238.5**	**1,861**
S75		BL07		A2	62.93	-		**1,895**
Reference wall panel		BL07		Low strength	2.00	-		**0,424**
S42	2	M1	2.42	A1	50.88	353	**74.7**	**0,583**
S46		M1		A1		353	**112.8**	**0,880**
S50		M1		G	87.88	273	**158.4**	**1,236**
S54		M1		A1	50.88	353	**95.8**	**0,748**
S58		M2	6.86	G	87.88	273	**181.9**	**1,419**
S62		M2		G		273	**196.6**	**1,534**
S66		BL07	38.58	G		542	**224.8**	**1,754**
S70		BL07		G		542	**259.8**	**2,027**
S74		BL07		A2	62.93	542		**1,798**
S41	4	M1	2.42	A1	50.88	353	**271.2**	**1,276**
S45		M1		A1		353	**184.1**	**1,437**
S49		M1		G	87.88	273	**125.2**	**0,977**
S53		M1		A1	50.88	353	**311.9**	**2,434**
S57		M2	6.86	G	87.88	273	**209.9**	**1,638**
S61		M2		G		273	**221.2**	**1,726**
S65		BL07	38.58	G		542	**324.2**	**2,530**
S69		BL07		G+A2	-	542	**327.9**	**2,559**
S73		BL07		A2	62.93	542		**1,650**
S40	6	M1	2.42	A1	50.88	353	**210.9**	**1,646**
S44		M1		A1		353	**232.4**	**1,814**
S48		M1		G	87.88	273	**183.4**	**1,431**
S52		M1		A1	50.88	353	**266.8**	**2,082**
S56		M2	6.86	G	87.88	273	**238.2**	**1,859**
S60		M2		G		273	**241.3**	**1,883**
S64		BL07	38.58	G		542	**275.9**	**2,153**
S68		BL07		G		542	**299.8**	**2,339**
S72		BL07		A2	62.93	542		**1,959**

Second group of specimens:

In the second group of specimens, there are six ½ scale, one story-one bay infilled reinforced concrete frames produced using various strengthening techniques. Some of these specimens are strengthened at the fabrication stage, while the others later on. The RC bare frame, Specimen #1, is essentially the first reference frame, and the reinforcement detailing of this specimen is given in Figure 4.

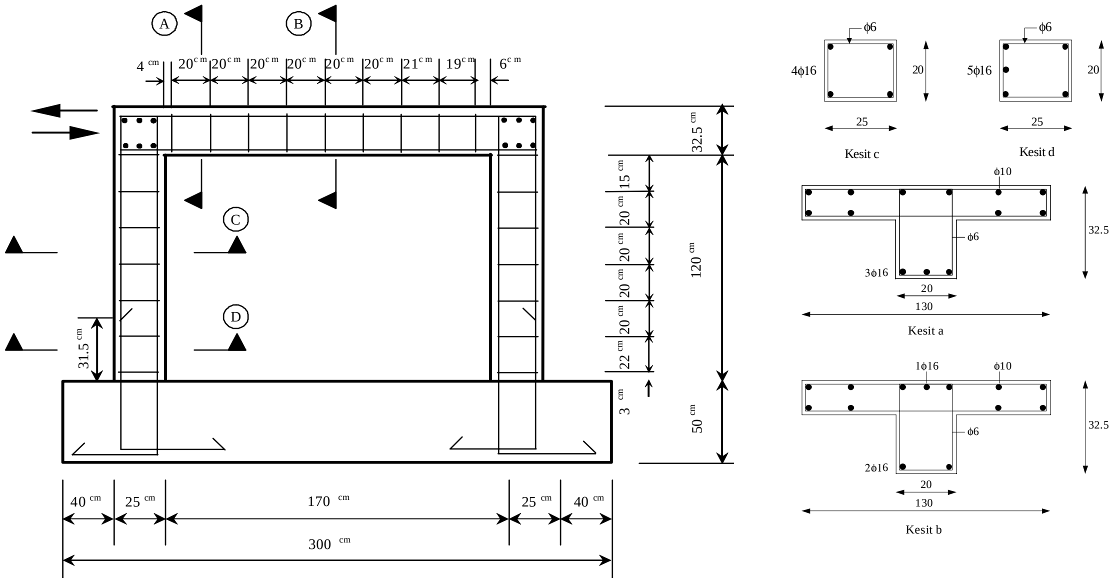


Figure 4. Reinforcement and the details of one story-one bay specimens

Another similar RC frame has been filled in a common way by brittle brick without having a serious connection in the interfaces between the wall and peripheral RC elements. This has been considered as the second reference frame, and named as Specimen #2, (Figure 5).

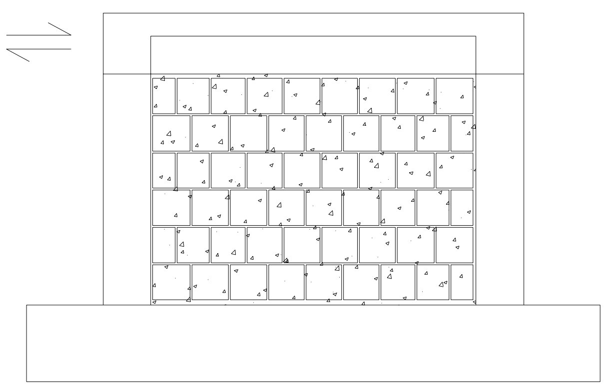


Figure 5. RC frame with brittle brick infill wall, Specimen #2

The infill wall of Specimen #3 is constructed prior to pouring the concrete into the form of beam and columns. Consecutive gaps are left between the contact surface of the wall and frame members. Full integration is provided between the infill wall and frame members by filling the gaps with concrete, while casting the frame, (Figure 6). Cyclic loading tests prove that substantial increment both in lateral stiffness, and strength is achieved, if full integration is provided between the infill wall and RC frame elements, (Figure 6). In this case the wall-frame combination will not suffer from separation or any kind of premature collapse during the earthquake.

Figure 6. Construction process of Specimen #3

Specimen #4 is made of low strength brittle bricks. The frame used in this specimen has been tested prior to constructing the brick wall for strengthening purpose. The gap between the wall and frame has been filled by concrete and shear connectors have been used between the frame and the infill material. Concrete and brick shear keys are supposed to transfer the shear between the filling concrete and brick wall. In other words, the wall in this specimen is constructed in the frame so that no contact exist before the gap left on purpose, is filled by concrete. Shear connectors are placed to the interface of new and old concrete parts. Before testing the specimen, it has been plastered with a thickness of approximately 10 mm. The same idea is used in the strengthening process of Specimen #5, which is infilled with high strength hollow block bricks without using any lateral and vertical reinforcement, (Figure 7). Specimen #51 and #52 are two identical specimens of this type.

Figure 7. General view of Specimens #4, #5

Specimen #4 has been strengthened after the first testing, by carbon fibers bonded only on the wall. In other words strengthening has been completed without touching the RC frame. This specimen is called Specimen #6. In the strengthening process, plaster on the wall is removed first, and then one layer of CFRP stripe is applied over the plain part of infill wall on both sides. CFRP stripes are not connected to the peripheral frame members, (Figure 8).

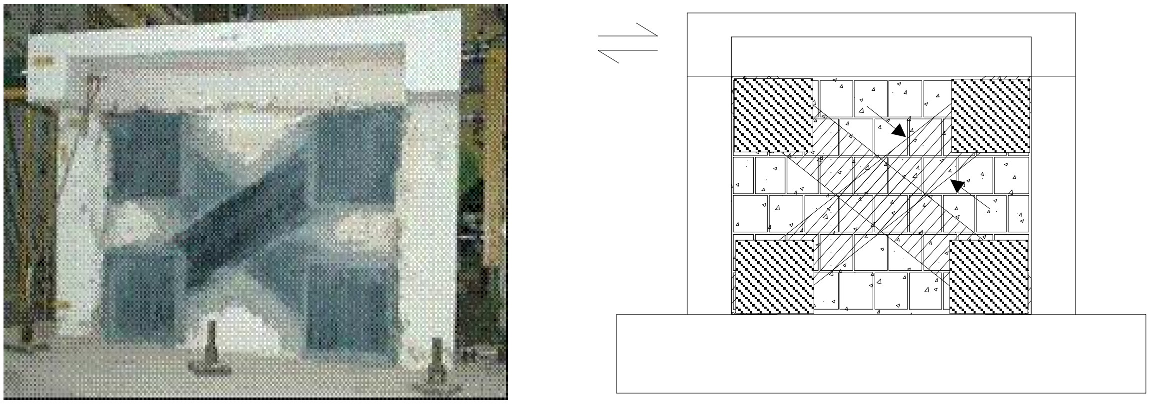
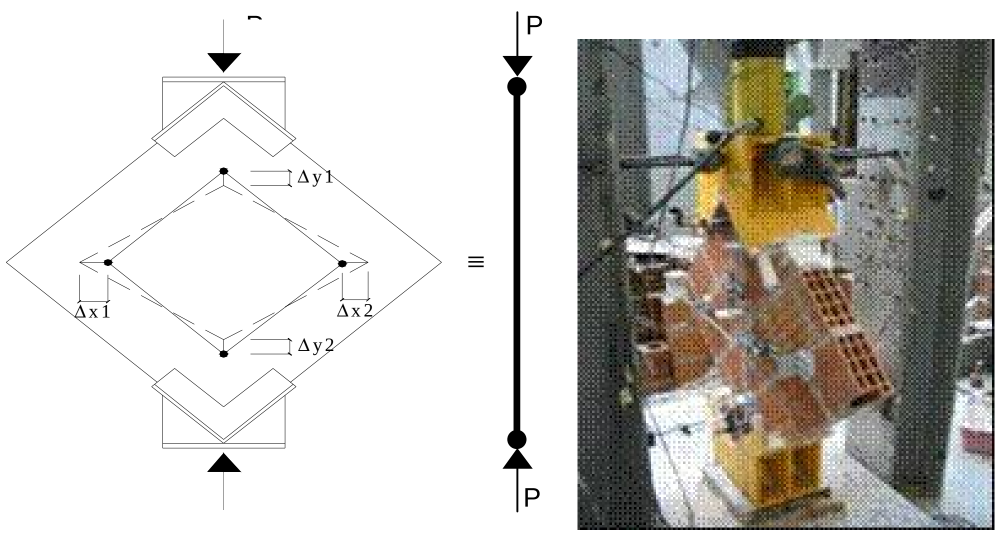


Figure 8. Specimen #6, RC infilled frame strengthened by CFRP stripes.

TESTING SETUPS AND MEASUREMENTS

First group of specimens:

The shear tests of wall panels are performed using a similar testing technique to the one described at ASTM C 1391-81 [5] with some modifications made according to the previous studies carried in I.T.U. 25 wall panel specimens have been tested so far. The testing setup for shear tests and the measuring details are shown in Figure 9a,b.



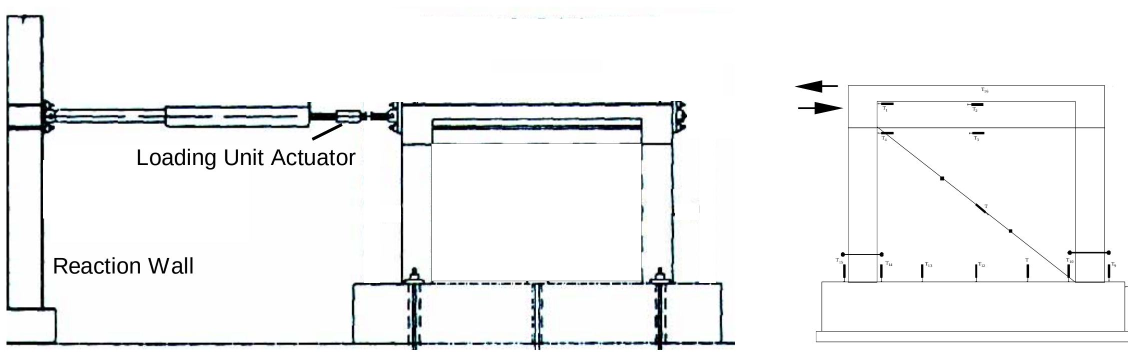
(a) (b)

Figure 9a,b. Testing setup of diagonal tension test

A force controlled testing technique is used with the intention of keeping the loading speed constant. 45-degree concentric diagonal loading is increased gradually until failure has been reached. Vertical and horizontal displacements, namely the shortening and elongations for each side of wall panel are measured using four transducers. Two more transducers are used in order to control the out-of-plane displacements. Displacement values from both sides of the specimens are measured at each load increment and the average of recorded measurements has been used in presenting the load versus vertical displacement curves (P-Δ). Failure modes and crack patterns have also been manually recorded during tests.

Second group of specimens:
A displacement-controlled testing technique has been used both in tension, and compression. An MTS actuator, ± 250 kN loading and ± 300 mm displacement capacity, is used for lateral loading. No axial force is applied to the columns. The target total displacement reached after each increment has been imposed to the structures three times, (Figure 15). Although there are many measurements from the special points of the specimens, the top displacement versus base shear relationships are selected to present here. The testing setup used for one story-one bay specimens is shown in Figure 10a.

The measuring system including the measurement for the relative displacements to foundation and the out-of-plane displacements is shown in Figure 10b.



(a) (b)

Figure 10a,b. Testing setup and measuring devices for one story-one bay specimen

TEST RESULTS

Test results achieved are presented below in two groups.

First group of specimens:
Load and displacements have been recorded at each load increment during the tests. Load-vertical displacement (P-Δ) and nominal shear stress-shear deformation (τ-γ) curves have been obtained using these data. The average values of vertical and horizontal displacements have been used while producing these curves, Erol [7], Erol [8]. The results that are presented below are reached by examining the P-Δ and τ-γ curves of wall panel specimens, evaluating the failure modes, and gathering the observations made during the tests. The relationships between applied force P and the average shortening Δ, (See figure 9a) have been given in Figure 11 for the specimens made of low strength ordinary brittle brick and for the specimens made of high strength bricks in Figure 13. Referring to those diagrams an equivalent nonlinear strut only with axial rigidity can be proposed for theoretical works.

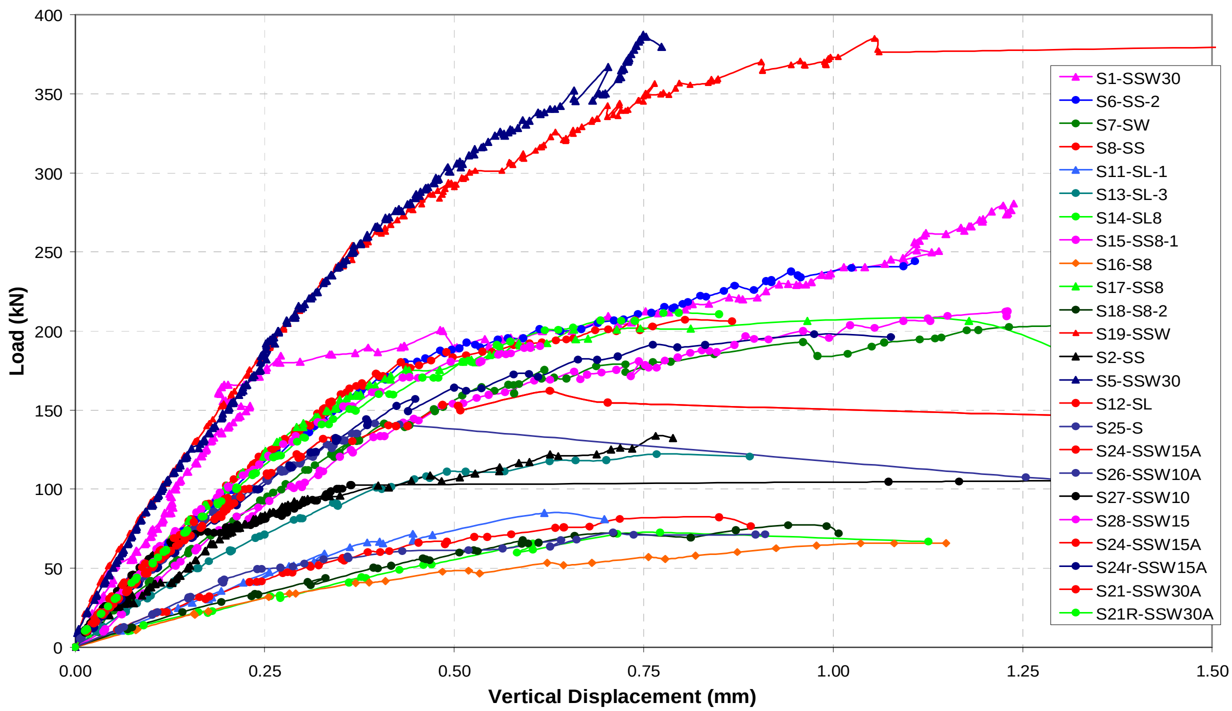


Figure 11. P-Δ curves for the specimens made of ordinary brittle bricks

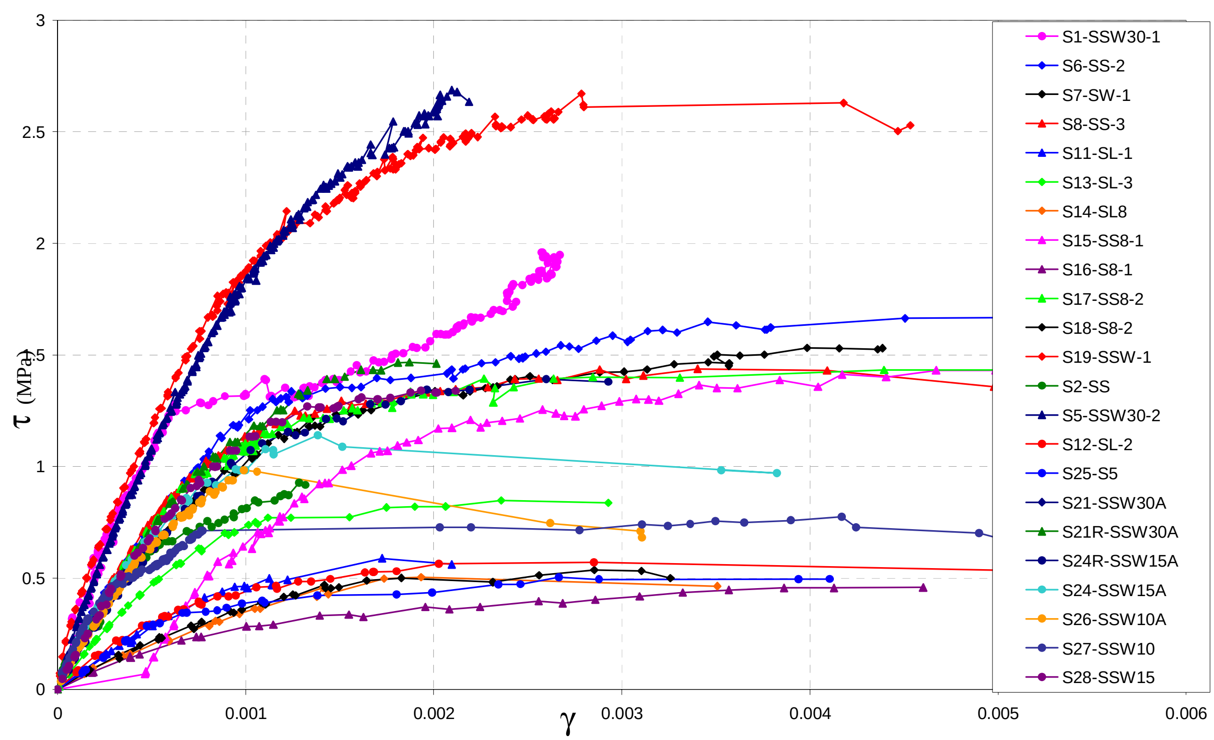


Figure 12. τ-γ curves of wall specimens made of ordinary brittle bricks

τ-γ curves experimentally obtained are all given in Figure 12 for the specimens made of ordinary brittle bricks and in Figure 14 for the specimens made of high strength bricks.

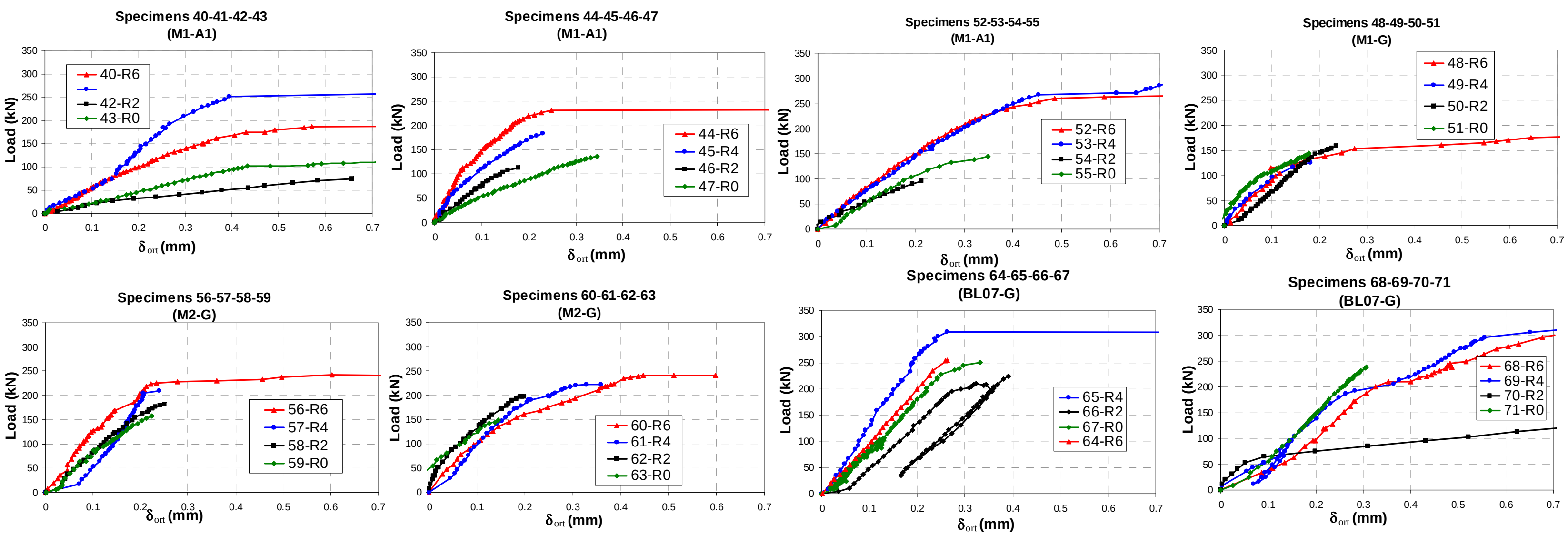


Figure 13. P-Δ curves of wall specimens made of high strength bricks

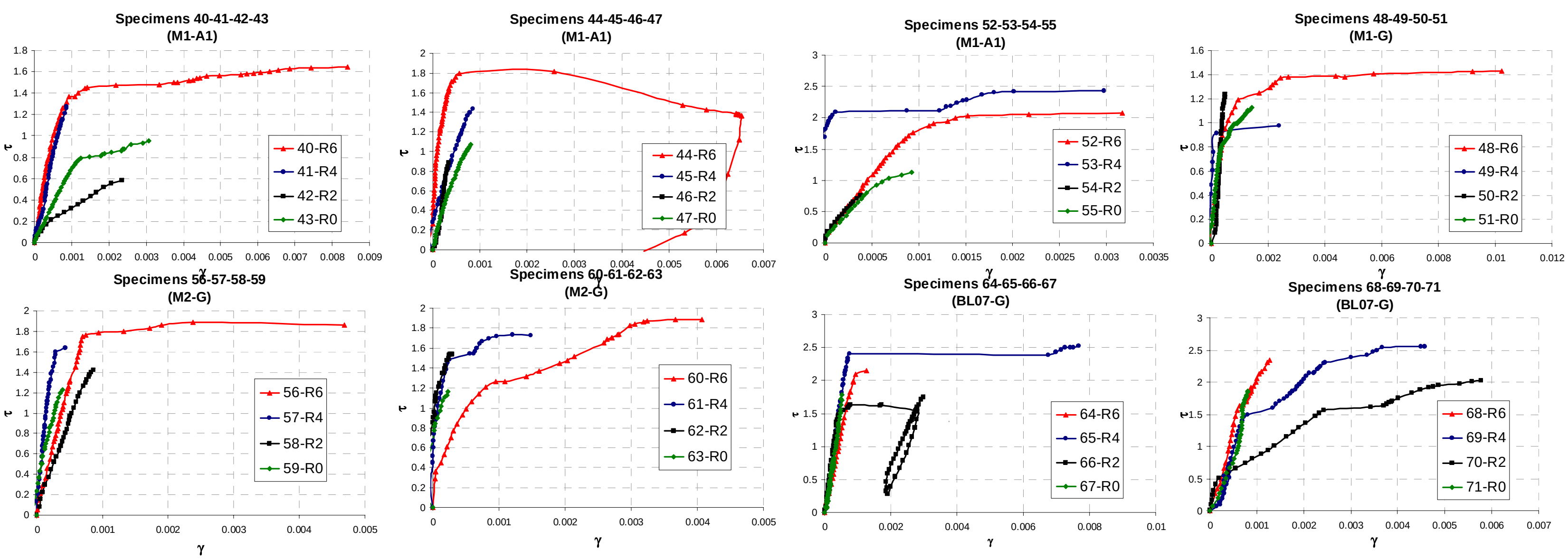


Figure 14. τ-γ curves for the specimens made of high strength bricks

Second group of specimens:
The displacement protocol given in Figure 15 has been followed, and the specimens shown in Figure 4-8 have been tested.

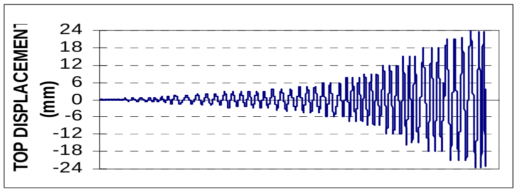


Figure 15. The displacement protocols used in the second group of specimens

The hysteresis loops and their envelopes achieved experimentally are presented in Figure 16 a,b,c,d,e.

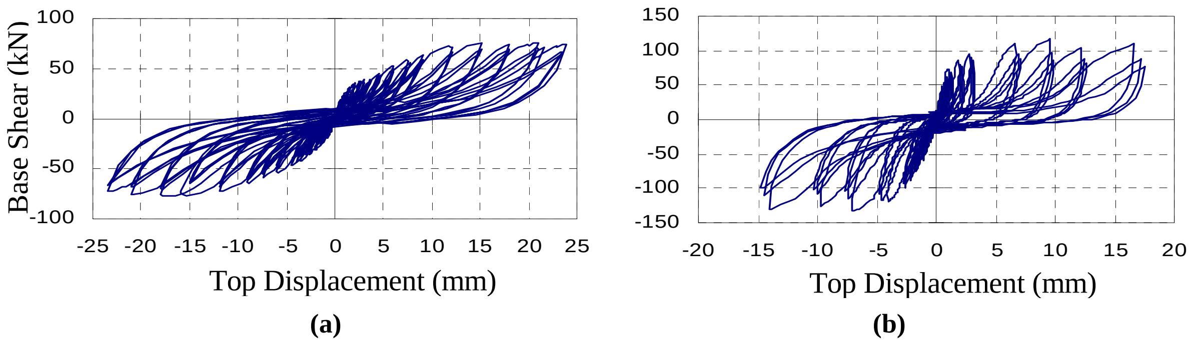


Figure 16a,b. The hysterisis loops of Specimen #1,2

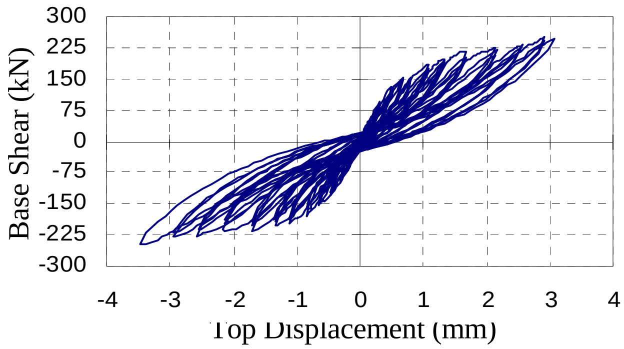


Figure 16 c. The hysterisis loop of Specimen #3

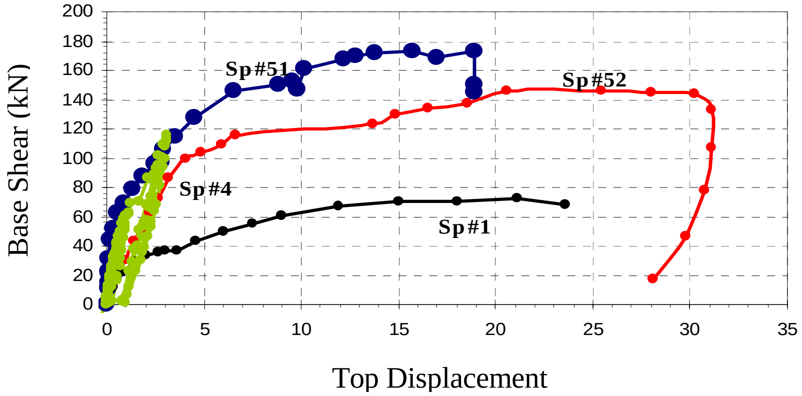


Figure 16d. The hysterisis loops of Specimen #4,5

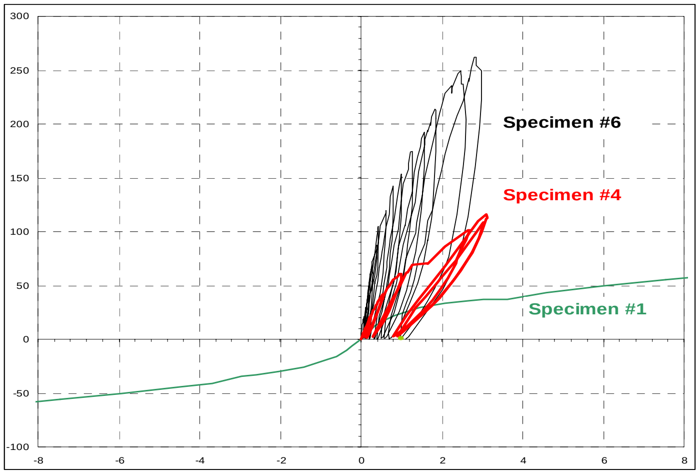


Figure 16e. The hysterisis loops of Specimen #6

The terms in Figure 16e and The failure mode of Specimen #6 can be seen in the Figure 17.

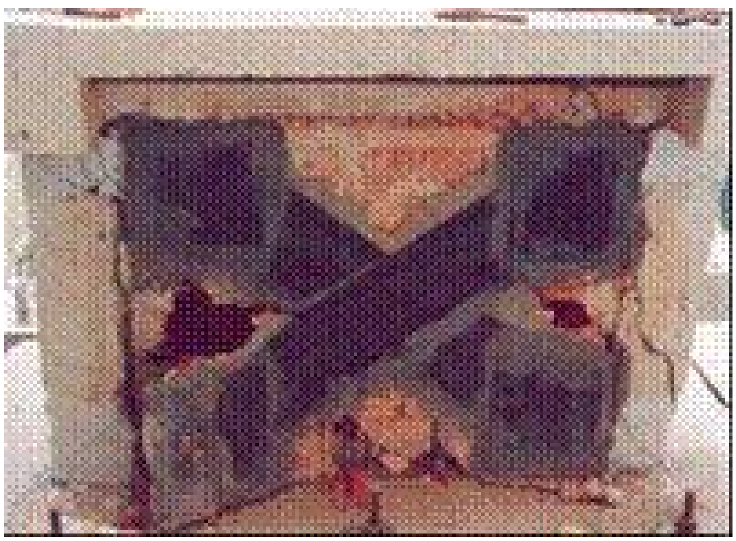


Figure 17. The failure mode of Specimen #6

RESULTS

Some of the conclusions achieved at the end of the tests are summarized below;

1. Although there are serious difficulties to perform the shear test of wall panels, the testing setup at I.T.U. has been modified several times so that the inevitable eccentricities of loading has been minimized and reliable deformations have been recorded from both sides of wall panels. The relationships between the load and diagonal shortening, P-Δ curve, and the shear stress and shear angle, τ-γ curves have been obtained respectively. These diagrams can be used to carry out the nonlinear analysis of RC frames infilled by similar material, after having smoothed the P-Δ curves. τ-γ curves can be referred in the stage of either design or redesign for upgrading

purposes of RC frames. If P-Δ or τ-γ curves are examined, it will be observed that plastering and CFRP application have substantial contribution to the strength and stiffness of brittle brick panels. Failure modes of panels are very much dependent on the existence of CFRP. Strength of panels is not proportional with the amount of CFRP bonded on the surface. However the CFRP shear connectors used between the two layers on each surface has relative importance on the behavior of panels.

2. Integration of infill wall and existing RC frame has tremendous effect on the overall behavior of infilled frames. This can be achieved either during the construction stage of original structure or afterwards for strengthening purposes.
3. The pilot tests have indicated that contribution of CFRP on the lateral load and energy consumption capacity of infilled frame is limited by the in-plane shear strength of hollow core brittle brick material widely used in some parts of the world. It is obvious that the existence of CFRP keeps the brittle wall to fall apart and hence contributes to the overall in-plane and out-of-plane stability of structure during the load reversals.

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