QUASI-STATIC TESTING OF ONE-BAY TWO-STOREY R/C FRAMES

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Abstract - The first tests on infilled frames at METU Structural Mechanics Laboratory were conducted at 1970's. In 1986, second experimental research program was initiated in which test frames were infilled with cast-in-place reinforced concrete (RC) infills. Third experimental research program was initiated jointly with Boğaziçi University in 1994. However, the introduction of cast-in-place reinforced concrete infill walls were not suitable for strengthening of the existing building stock, since it involved messy construction works and requires evacuation. With the financial support of NATO, a new experimental research program was initiated in 2001, to develop such innovative non-evacuation retrofitting techniques, suitable for the most common type of building structures in the region.

For years, one-bay two-storey specimens, called "twin frames", were tested in the laboratory. In these tests, the specimens were tested horizontally. This set-up had been developed with the rather modest facilities available in the laboratory, and required a lengthy and tedious testing process. Since one of the aims of the study, supported by NATO Project, was to modify the test set-up for one-bay two-storey frames, a new test set-up had been developed to be used for the future studies. In the new test set-up, specimens were tested vertically. These specimens were supposedly identical to the twin frames used in the previous test series. Since experimental study is time consuming and expensive, test specimens were designed and detailed carefully, construction of the test specimens were planned considering all the details, instrumentation were designed considering the main objectives. After the two preliminary tests were conducted, modifications were done and new apparatus were added on the new set-up. In this study, both set-ups, the modifications and added apparatus are explained in details.

Index Terms - **Infilled frames, cast-in-place reinforced concrete infills, strengthening, construction works, non-evacuation retrofitting techniques, experimental study, instrumentation, preliminary tests, modification, apparatus.**

I. INTRODUCTION

For many years, structures having inadequate lateral strength and stiffness were strengthened by applying RC infills. The first tests on infilled frames were conducted at 1970's at METU Structural Mechanics Laboratory. One-bay, one-storey infilled frames were tested under lateral loads increasing monotonically.

In 1986, with the initiation of the second experimental research program, "twin frames" were started to be used. [1]. This set-up had also been used during the the third experimental research program [2, 3].

Infilling of frames by means of cast-in-place RC infills had been widely used. Many buildings were repaired or strengthened with this method, especially after major earthquakes. However, there are some drawbacks of cast-in-place infill wall strengthening technique. The application requires heavy construction work, so it is necessary to evacuate the building. The workmanship in this rehabilitation method is difficult and time-consuming [4, 5]. Cast-in-place RC infill wall application is naturally very suitable for post-quake strengthening applications of damaged buildings that are already evacuated. There are conditions where cost, time and working space constraints limit the building operations which result in dictating other solutions. With the financial support of NATO, a new experimental research program was initiated in the year 2001, to develop such innovative non-evacuation retrofitting techniques, suitable for the most common type of building structures in the region, by eliminating the use of large formworks and large quantities of fresh concrete.

For years, one-bay, two-storey specimens, called twin frames by Smith [6], were tested in METU Structural Mechanics Laboratory. This test set-up was first used by Altin [1]. This arrangement consisted of construction of two frames connected with a relatively rigid beam called foundation beam in order satisfy the rigid foundation condition. In these tests, the specimens were tested horizontally.

Since one of the aims of the NATO project [7, 8, 9] was to modify the test set-up for one-bay two-storey frames, a new test set-up had been developed to be used for the future studies. In the new test set-up, specimens would be tested vertically. Since experimental study is time consuming and expensive, test specimens were designed and detailed carefully, construction of the test specimens were planned considering all the details, the instrumentation were designed considering the main objectives for this project.

II. NEED FOR DEVELOPING A NEW TEST SET-UP

A. Test Set-up for Twin Frames [3]

Test specimens of "Twin Frames" were one-bay, two-storey RC frames under vertical and reversed-cyclic lateral loading simulating earthquake effects. For this purpose, twin specimens were constructed with a common foundation beam at the mid-section. These twin specimens were cast together and tested at the same time.

The test specimens were placed between the two reaction beams that were connected to each other with steel tie beams. The specimens were tested in the orizontal position. The horizontal movement of the specimens was enabled by steel plates moving freely on ball bearings. Loading and support conditions were arranged symmetrically. However, in the calculations, frictional forces between the plates and balls were considered to be negligible.

The testing system consisted of reaction beams, loading equipment, instrumentation and a data acquisition system. The reaction beams were 400×800×4600 mm RC blocks, and they are connected to each other by means of four steel tie beams. The lateral load was applied at the foundation beam through the hydraulic jacks as presented in Figure 1. Hence, reaction forces at each end of the twin specimens were the lateral loads applied at the top storey level. The forces acting on the test specimens are presented in Figure 2. In each half cycle, the direction of the lateral loading was changed. The magnitude of the applied a load was measured with load cell that was connected to the jack and the data acquisition system.

Specimens were instrumented to measure the displacements and rotations of the frame; and shear deformations in the reinforced concrete infills. In Figure 3, the position of the dial gages (DG), and linearly variable displacement transducers (LVDT) are presented.

The lateral deformation of the specimens was measured by means of transducers. Two LVDT's were mounted to the second floor, one to the first floor level and one to the foundation level. These transducers measured the lateral displacements and support settlements. Two LVDT's were mounted to the foundation beam, perpendicular to the loading direction, to measure the rotation of the foundation beam. In the calculation of the lateral deflection at each storey, beams were assumed to be inextensible in their longitudinal direction. Hence, corrections were made only for the actual lateral deformations resulting from rigid body rotations and support settlements. Calculation of the lateral deflections is given in Figure 4.

Considering the lengthy and complex calculation process, the expense of the test frames for being twins and the error introduced during the lateral deflection calculations, a new test set-up for one-bay, two-storey frames came out to be obligatory to be developed for the future studies, in which specimens would be tested vertically. These specimens were supposedly identical to the twin frames used in the previous test series, as shown in Figure 5.

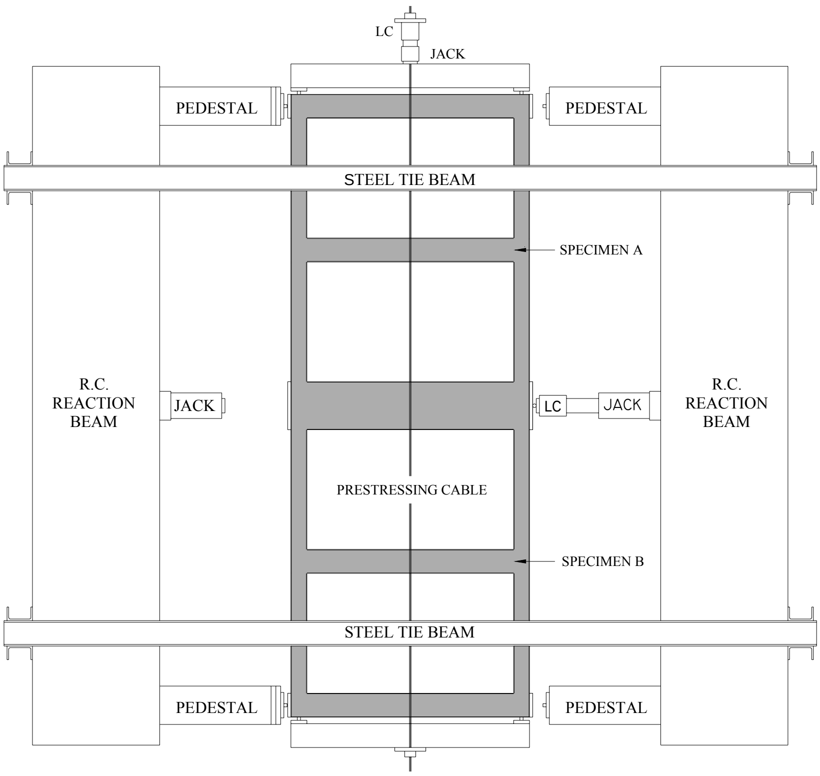

Figure 1. Test set-up of twin frames

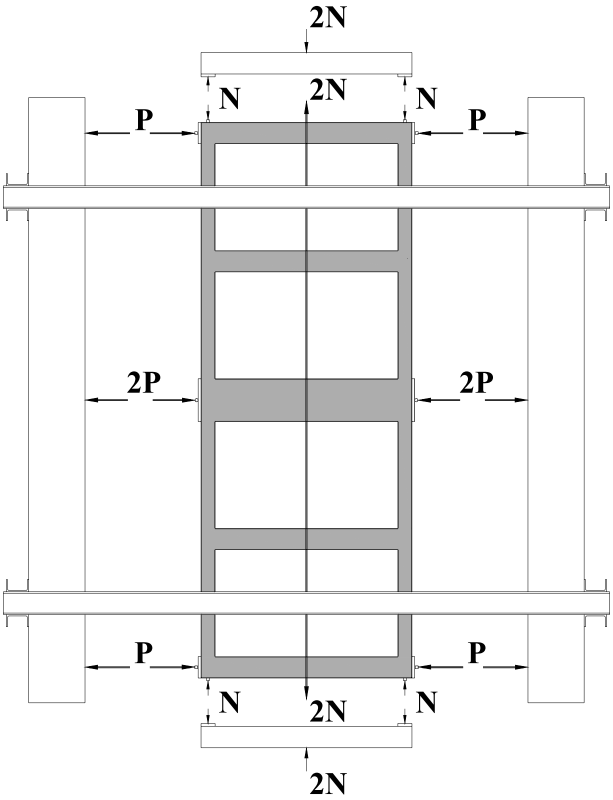

Figure 2. Forces acting on the twin frames

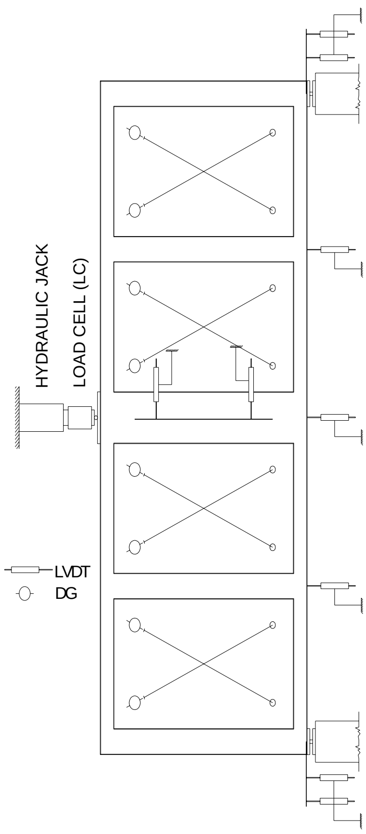

Figure 3. Instrumentation of twin frames

Loading of the specimens to some predetermined level and then unloading it constituted a half cycle. In each half cycle (starting from zero loads) the direction of the loading was reversed. The place of the load cell had to be changed for each half cycle. In the calculations, the rotations around the relatively rigid foundation beam had to be calculated, resulting with a lengthy and complex calculation process. Since there were two frames tested in the test set-up, the calculations and analysis were made for one of the frames in which major damage took place. Also, the crack pattern at the back of the specimen could not be visible during the tests.

B. Newly Developed Test Set-up

i. Test Frames

The vertical test set-up used in the present test series was recently developed and employed, hoping that it would be identical to its sister lying down on the floor. For this purpose, two preliminary tests [7] were conducted to verify the proper functioning of the test set-up. The specimens were tested under reversed cyclic lateral loading. The frames of the specimens had the deficiencies common in most of the building frames in Turkey. The aforementioned deficiencies are insufficient lateral stiffness, non-ductile members, bad detailing and low concrete quality. Dimensions and reinforcement of the test frames are illustrated in Figure 6.

ii. Materials

A low strength concrete was deliberately used in the test frames to represent the concrete commonly used in existing building structures. Both the first and second floor frame bays are infilled with scaled hollow bricks, illustrated in Figure 7, covered with a scaled layer of plaster at both faces. Ordinary cement-lime mortar was used for the plaster, reflecting the usual practice. The infilling method is shown in Figure 7. Ordinary workmanship was intentionally employed in wall construction and plaster application to reflect the ordinary practice. For the same reason, mild steel plain bars were used as reinforcement in both test frames.

iii. Test Set-up, Loading System and Instrumentation

Figure 8 gives a general view of the new test set-up. As seen in this figure, tests are being performed in front of the reaction wall. Test units are subjected to reversed cyclic horizontal load resembling the seismic effects.

An RC universal base, serving as a rigid foundation for the test unit and enabling various support configurations, has been prestressed to the strong testing floor of the laboratory. Each test frame is cast together with a rigid foundation beam, which is suitably bolted down to the universal base as required. The quasi-static test loading consists of reversed cyclic horizontal load applied at floor levels, besides constant vertical load approximately equal to 20% of the column axial load capacity.

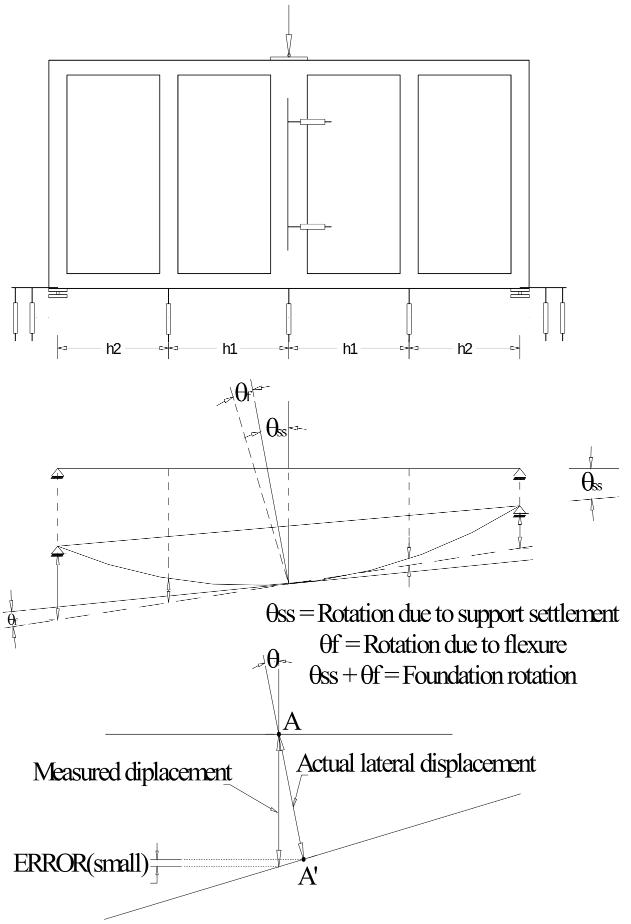

Figure 4. Calculation of the lateral deflections (twin frames)

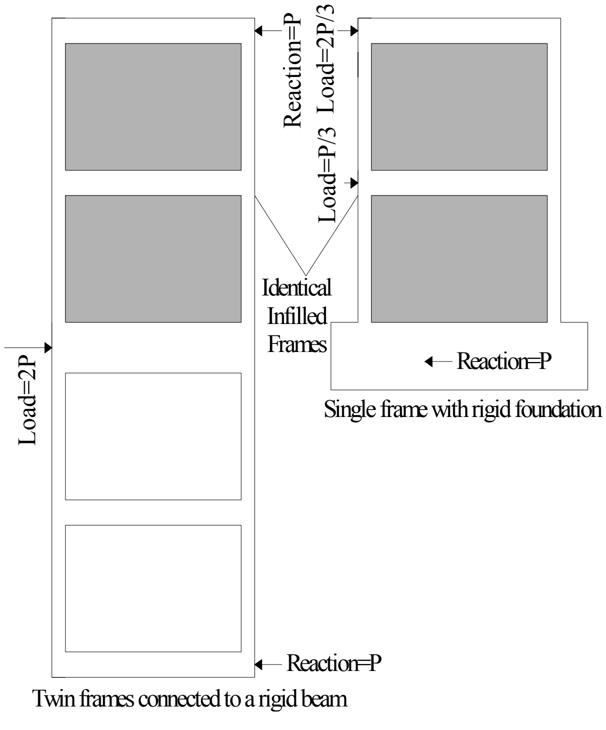

Figure 5. General view of the old and new test specimens

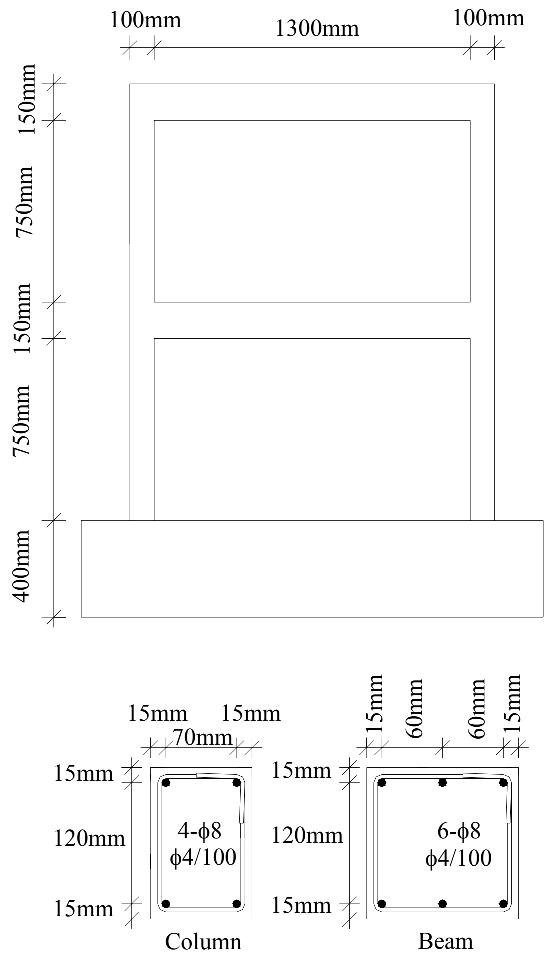

Figure 6. Dimensions and reinforcement of the test frames

Reversed cyclic lateral loading was applied by using a double acting hydraulic jack which was capable of applying 600 kN in compression and 420 kN in tension. A load cell was connected between the hydraulic jack and the test frame to measure the magnitude of the applied lateral load. The capacity of the load cell was 600 kN in compression and 300 kN in tension. An adapter made from strong steel was used to connect the hydraulic jack and load cell. The lateral loading system had pin connections at both ends to eliminate any accidental eccentricity mainly in the vertical direction and tolerating a small rotation in the horizontal direction normal to the testing plane.

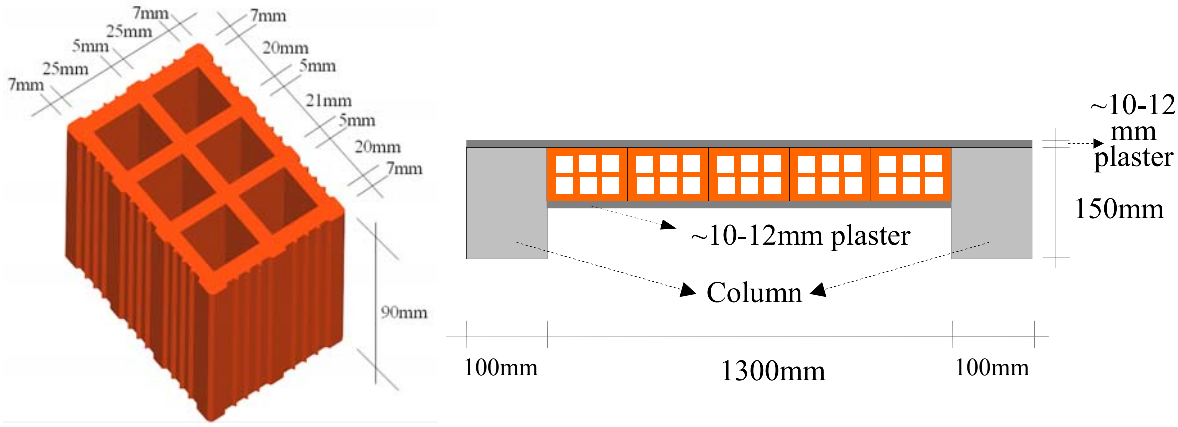

Figure 7. Hollow Brick Used as Infill Material and Infilling Method

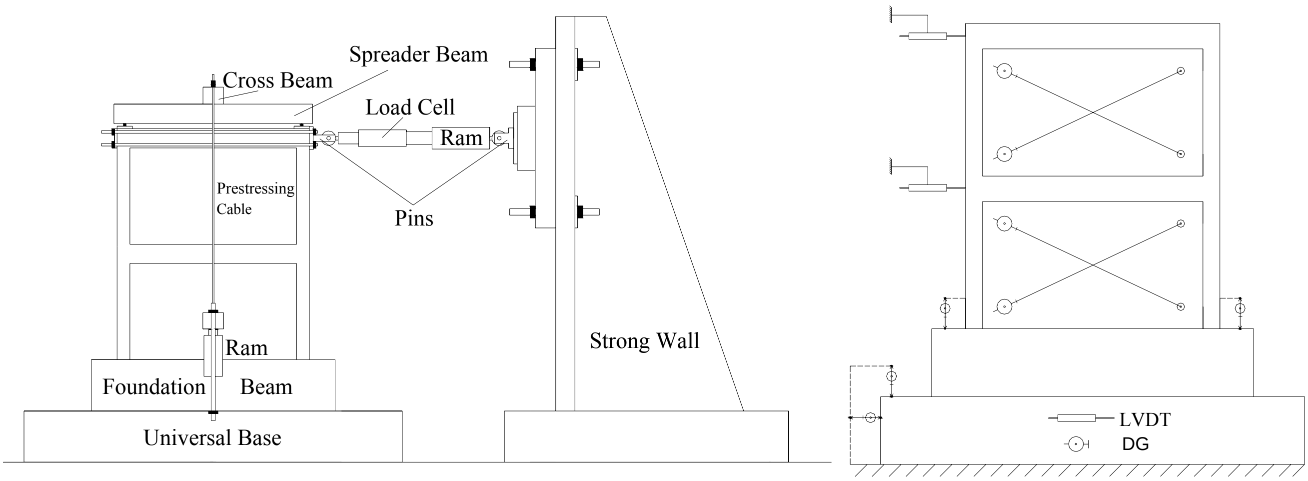

Figure 8. General view of the newly developed test set-up and instrumentation

The vertical load application gear consisted of a hydraulic jack and a load cell placed between a spreader beam and a cross-beam at the top, which was pulled down by two prestressing cables attached to the universal base on either side of the test unit. Having been supported as a simple beam with supports at the column heads as shown in Figure 8, the spreader beam divided the load and transferred two equal components to the two columns. The load was continuously monitored and readjusted during the test.

Displacement measurements taken at the column roots are meant for computation of rotations of the entire test unit, when the infill wall remains intact and the overall behaviour of the test unit resembles cantilever behaviour. However, they also provide data for monitoring the critical column section deformations; steel yielding in the tension side column, concrete crushing in the compression side column etc. Although it is heavily prestressed to the strong testing floor, the rigid body rotations and displacements of the universal base are monitored using four dial gauges, during the tests to enable corrections in the critical measurements in the case of an unexpected movement. Instrumentation is shown in Figure 8.

III. Experimental Results

A.Behavior of Test Specimens

Drift ratio – lateral load graphs for both stories of the first preliminary test specimen and photograph of the test frame after the test is shown in Figure 9 and 10, respectively. In both figures, it can clearly be seen that major damage took place in the second storey infill wall despite the expectation of failure in the first storey, which has always been the case in the twin frames. For years, similar tests have been performed on horizontally tested twin frame specimens. Although this loading pattern did not reflect the earthquake effect realistically, it was naturally an approximation to simplify the test procedure, and it had never caused a problem of this kind in the old horizontal test set-up. The first preliminary test proved the contrary.

After discussions, it was concluded that the unexpected type of failure was stemming from the different reaction types developing at the foundation level for the horizontal and the vertical test setups. The reaction was a concentrated force acting at the opposite end of the foundation beam of the twin frames, whereas it was distributed along the entire length of the foundation beam in the vertical test set-up, leading to a much wider compression strut development in the first storey infill wall. Since equal shear forces developed in both infill walls under the horizontal force applied at the top, the lower one had a higher chance to survive [6]. The phenomenon is shown in Figure 11.

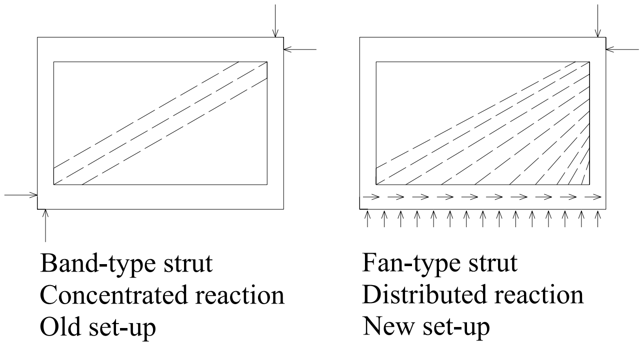

Figure 11. Reaction types developing at the foundation level

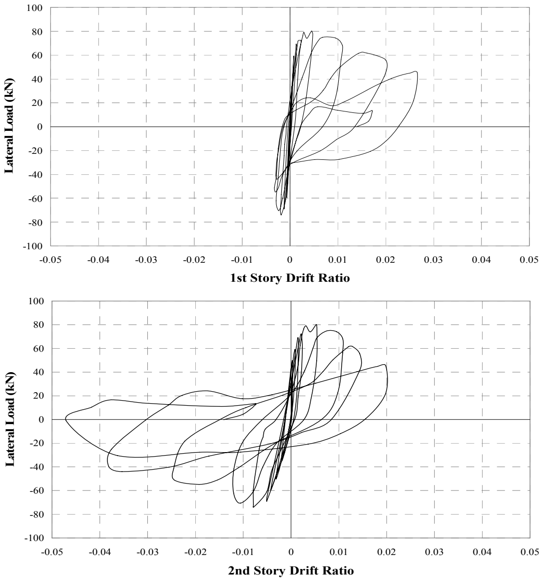

Figure 9. Drift ratio-lateral load graphs for both stories (Specimen PPR1)

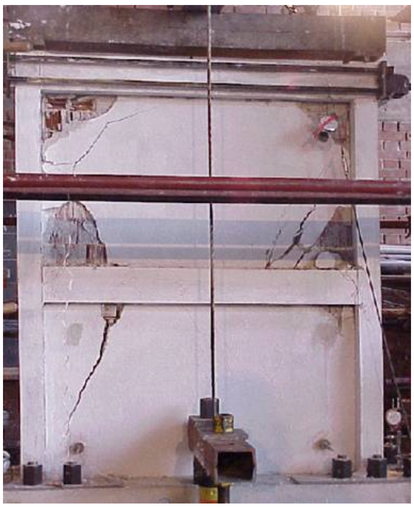

Figure 10. Test Specimen PPR1

In the second preliminary test, the same loading pattern was used. At the second floor level, clamps made of four steel bars connected to two loading plates at either end are loosely attached to the test frame to avoid from any unintended interference with the frame behaviour, which may possibly be caused by the external prestressing on the top beam. Thus, in both pushing and pulling modes, a horizontal push is applied to the test unit through steel loading pads without inducing any undesirable axial load in the beam. In the first cycles, same behaviour was observed. In the later cycles, out-of-plane deformations were observed due to unsymmetrical infill placement and application of load in plane of symmetry. The north column broke-off at the fist storey beam-column joint and the test was terminated. Out-of-plane deformations had to be prevented and the lateral load application had to be modified in order to reflect the earthquake effect in a more realistic way. Drift ratio – lateral load graphs for both stories of the second preliminary test specimen and photograph of this specimen after the test are shown in Figure 12 and 13, respectively.

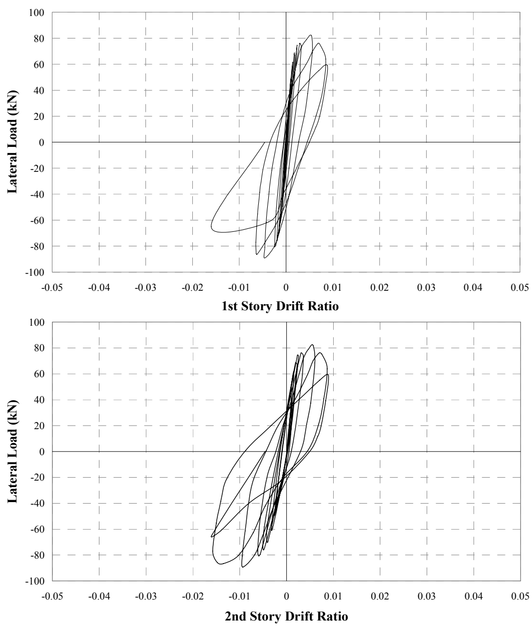

Figure 12. Drift ratio-lateral load graphs for both stories (Specimen PPR2)

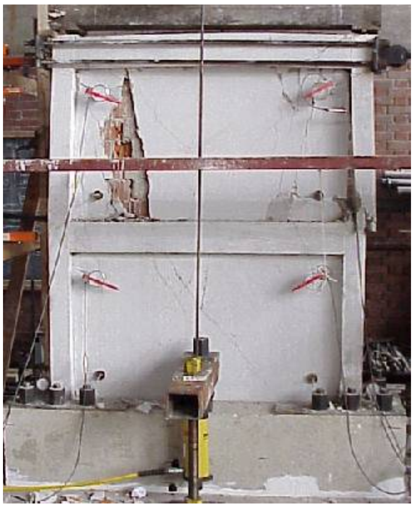

Figure 13. Test Specimen PPR2

During the test, it was observed that one of the problems was caused by unsymmetrically placed infill walls leading to eccentric loading, which created out-of-plane deformations. The infill wall, which has a considerably smaller thickness than the beam width, is placed eccentrically on the exterior side of the beam to reflect the common practice. Thus the contribution of the infill makes the frame behaviour somewhat unsymmetrical, and the load applied in the plane of symmetry creates warping, which may lead to significant out-of-plane deformations, especially towards the end of the test. A rather rigid external steel 'guide frame' attached to the universal base, was used to prevent any out-of-plane deformations. Four 'guide bars' two on each side, with roller ends, are attached to the guide frame, and they gently touch the test frame beam, smoothly allowing in-plane sway. The photograph given in Figure 14 shows the guide frame and the guide bars.

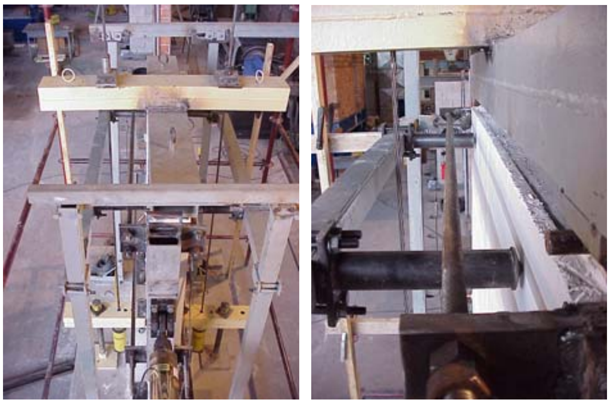

Figure 14. Guide frame and guide bars

The other problem could be solved by using a much more realistic two-component horizontal load, applied at each of the two floor levels, the second floor receiving twice the load as the first floor. At floor levels, clamps made of four steel bars connected to two loading plates at both ends were loosely attached to the test frame. At the spreader beam side, loading plates at both floor levels were welded to the spreader beam. Before test, the clamps were carefully controlled to be loose not to make any external prestressing on the beams. The last form of the new test set-up, with lateral load sharing apparatus between the floors, is given in Figure 15.

After adding the guide frame and the guide bars to be a remedy for the eccentric loading caused by unsymmetrically placed infill walls and the spreader beam, distributing the lateral loading so that the second floor receiving twice the load as the first floor, to be a remedy for reflecting the earthquake effect more realistically, first successful test was performed.

A specimen representing the present state of a typical existing building, an ordinary reinforced concrete frame with hollow brick infill walls plastered on both sides, was tested under reversed cyclic loading to serve as a reference for the behaviour and capacity of the strengthened specimens to be tested. Drift ratio – lateral load graphs for both stories of the first test specimen given in Figure 16 displays clear indications of the hollow masonry infilled frame behaviour characterized by,

- Rather rigid and linearly elastic behaviour at the initial stages under relatively high loads,
- Relatively high capacity resulting from infill wall contribution,
- Rapid strength degradation and very rapid stiffness degradation upon infill wall crushing.

This expected behaviour was concluded by a typical failure accompanied by excessive permanent first storey sway deformations as illustrated in Figure 17.

Maximum lateral forward and backward loads and the corresponding drift ratio values for both storeys of the test specimens are given in Table 1.

B. Shear Deformations in the Infills

Lateral load-both storey shear displacement curves of all specimens are presented in Figure 18. As seen in this figure, shear deformation on the first storey infill wall was less as compared to that of the second storey infill wall, for both preliminary specimens. After introducing the guide frame - the guide bars and the spreader beam, major damage took place in the first storey infill wall, as expected. Shear deformations on both infill walls of the first preliminary test specimen could not be collected towards the end of the test and this was resulted from debonding of the dial gauges due to localized effect of concrete crushing on both infill walls. As can be sen from Figure 18, the shear displacement of the first storey infill wall of Specimen PR-1 was greater than that of the second storey meaning that major damage took place on the first storey infill wall, as expected. This behaviour were not observed in the tests of the two preliminary test specimens.

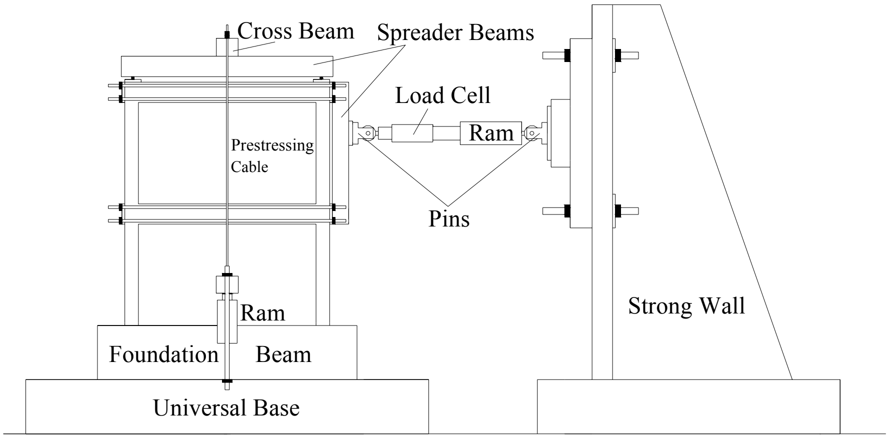

Figure 15. General view of the newly developed test set-up (last form)

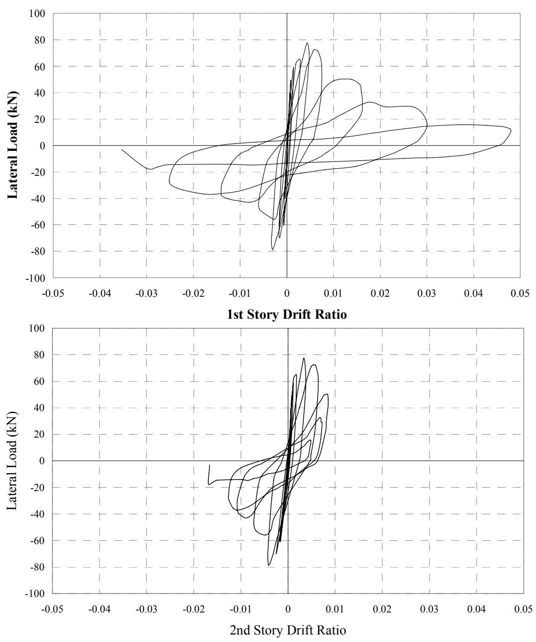

Figure 16. Drift ratio-lateral load graphs for both stories (Specimen PR1)

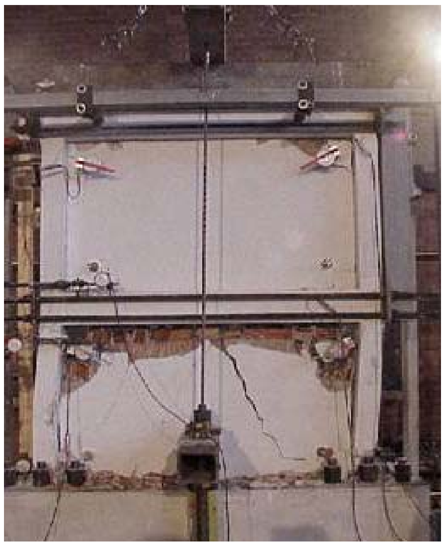

Figure 17. General view of the Specimen PR1 at the end of the test

IV. CONCLUDING REMARKS

1. After adding the guide frame and the guide bars for the eccentric loading problem and the spreader beam for distributing the lateral loading in between the both stories, the newly developed test set-up seemed to be consistent and satisfactory for the conduction of successful tests.

2. In the new set-up, specimens were cast horizontally. After hardening of the concrete, they were lifted up to be stand vertically. In this position, hollow brick infill walls were constructed, plastered and the specimens were white-washed easily. During the tests of the specimens, cracks on infills and on the RC infills on both sides were easily observed. However, in the old test set-up, there was no possibility to observe the cracks on bottom side of the specimen during the test since it was tested horizontally.

3. In the old set-up, lateral loads were applied to the second storey levels only. In the new set-up, lateral loads were applied such that second floors receiving twice the load of first floors, which simulated the earthquake loading much more realistically.

4. In the old set-up, experiments lasted longer since the direction of the load cell had to be changed for each half cycle, which resulted with lengthy and tedious testing process together with complex calculation process.

5. In both set-ups, frictional forces between the steel plates and the ball bearings were ignored for simplicity.

6. In the old set-up, there was twice number of displacement transducers as compared to new set-up,

since there were two test specimens. Calculations and analysis were made for one of the frames in which major damage took place. This necessitates the importance of the care to be paid for the damage observation.

7. For the new set-up, the resulting deformations, measured at numerous locations to obtain data, were adequate needed for a comprehensive analytical evaluation of the performance.

Table I
MAXIMUM LATERAL LOADS AND CORRESPONDING DRIFT RATIO VALUES

Specimen	Max. Forward Load (kN)	First Storey Drift Ratio δ/h	Second Storey Drift Ratio δ/h	Max. Backward Load (kN)	First Storey Drift Ratio δ/h	Second Storey Drift Ratio δ/h
PPR1	80.16	0.0045	0.0053	74.09	0.0018	0.0078
PPR2	82.05	0.0054	0.0057	89.25	0.0046	0.0093
PR1	76.81	0.0042	0.0033	78.78	0.0030	0.0041

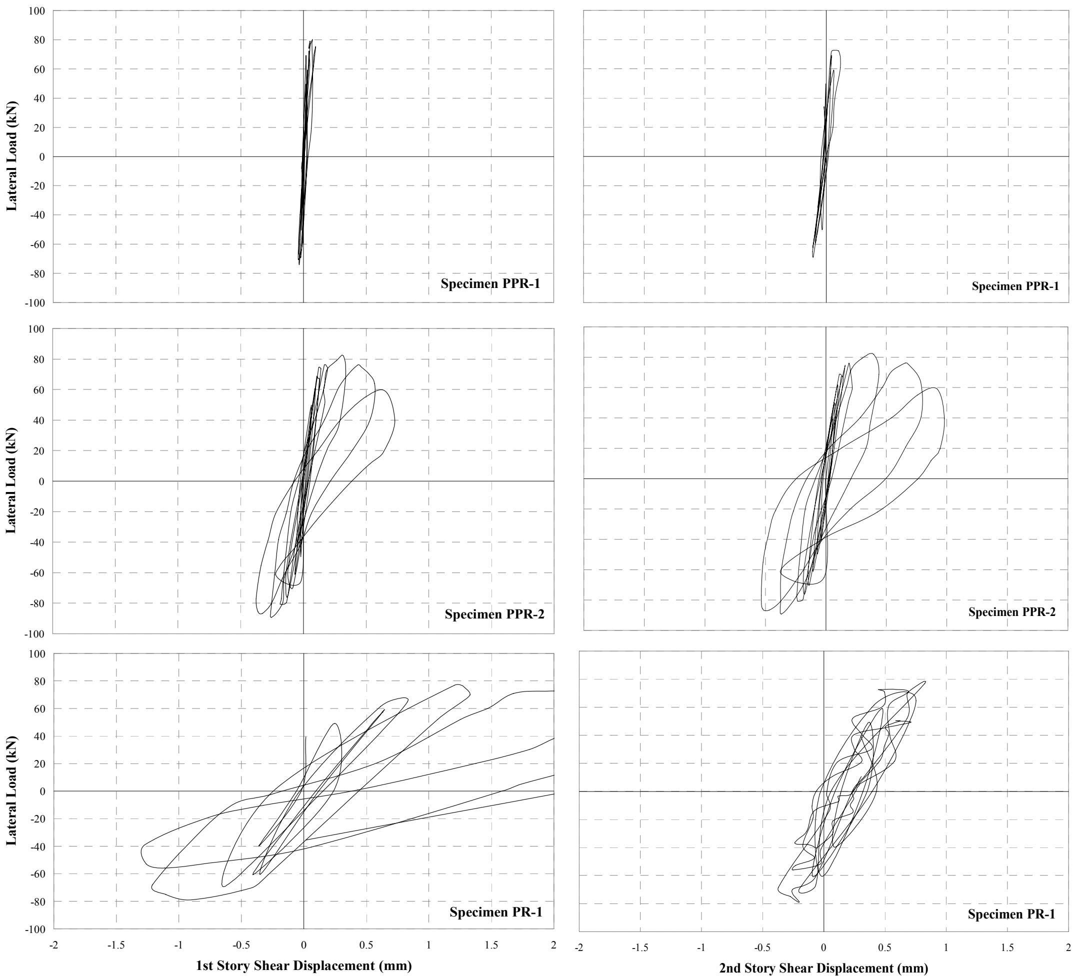

Figure 18. Infill wall shear displacements – Lateral load graphs of the test specimens

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