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Earthquake Performance Upgrade of Infilled Nonductile RC Frames With External Mesh Reinforcement and Plaster

By

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Abstract:

The objective of this paper is to report the result of an experimental program conducted on the strengthening of nonductile RC frames by using external mesh reinforcement and plaster composite. The main objective was to test proposed strengthening technique for reinforced concrete buildings, which could be applied with minimum disturbance to the occupants. Generic specimen has two floors and one bay RC frame in ½ scale. Six specimens, two of which were reference specimens and the remaining four of which had deficient steel detailing and poor concrete quality were strengthened and tested under cyclic loading. The parameters of the experimental study are; mesh reinforcement ratio and plaster thickness of the infilled wall. Externally reinforced infill wall composites improve seismic behavior by increasing lateral strength, lateral stiffness, and energy dissipation capacity of reinforced concrete buildings, and limit both structural and nonstructural damages caused by earthquakes.

Keywords:

Mesh reinforcement, plaster, earthquake, frame, strengthening.

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1. Introduction:

In Turkey a great number of reinforced concrete (RC) structures had totally collapsed or were severely damaged due to recent six major earthquakes causing loss of human lives. For most existing RC buildings seismic behavior was inherent in the structural system and under lateral loading, such as earthquakes, owing to excessive interstory drift. In collapsed structures several detailing and construction mistakes, such as failures of beam-column connections, spalling of column end regions, buckling of column longitudinal reinforcement, low concrete quality, nonseismic reinforcement details were observed. Also, strong beam-weak column joints are prone to story failures. Widely-spaced ties, irregular designed structural systems are common (Kara, 2006). Longitudinal reinforcement in columns normally was lap-spliced with short length just above the floor level. Joint transverse reinforcement was not common and member ends are not properly confined. Transverse reinforcement generally included hoops with 90-degree bends and those stirrups have wide spacing. Column transverse reinforcements were not exist along the beam-column joints.

Following the 1999 Marmara earthquake in which more than 20 000 people died, urgent necessity for improving the seismic resistance of RC framed structures is obvious. A new strengthening method presented in the TDY2007 is the use of external mesh reinforcement and plaster over the infills. This method of rehabilitation is expected to be more feasible and not disturbing function of the building and occupants. Since this proposal is new for Turkish engineers and researchers, only few experimental studies exist in the literature. The main concept of this paper is to investigate the behavior of the seismic strengthening method by bonding mesh reinforcement with plaster on hollow brick masonry infill walls. The aim is to convert the infill into a load carrying system acting as a cast-in-place concrete shear wall. The benefit of the method is increase the stiffness of the frames and to improve the seismic performance of poorly constructed RC frames with decreasing the time and the workmanship and minimum disturbance to the occupants. The earthquake performance of the buildings with poor construction details can not be satisfactory due to the high value of drift [1]. The proposed method should be convenient in terms of the materials and workmanship so that a huge number of vulnerable buildings can be retrofitted against earthquakes [2].

2.Experimental Program

In current research six specimens were prepared with identical geometric dimensions, reinforcement patterns and materials used. Specimens were tested at Structural Mechanics Laboratory of Selcuk University. The test frame was a 1/2-scale, one-bay, two-storey nonductile RC frame. In order to prevent wrong interpretations of the experimental results, the model ratio was chosen as close to 1/1 as possible. The height of one storey was 1500 mm and length of the specimen was 2360 mm. The columns dimensions were 160 x 240 mm, the beams dimensions were 240x240 mm. In columns, four 12 mm diameter longitudinal reinforcement and in beams six 12 mm diameter plain bars were used. Plain bars with a diameter of 8 mm spaced at 150 mm were used as ties. Dimensions and reinforcement details of the test frames are given in Figure 1.

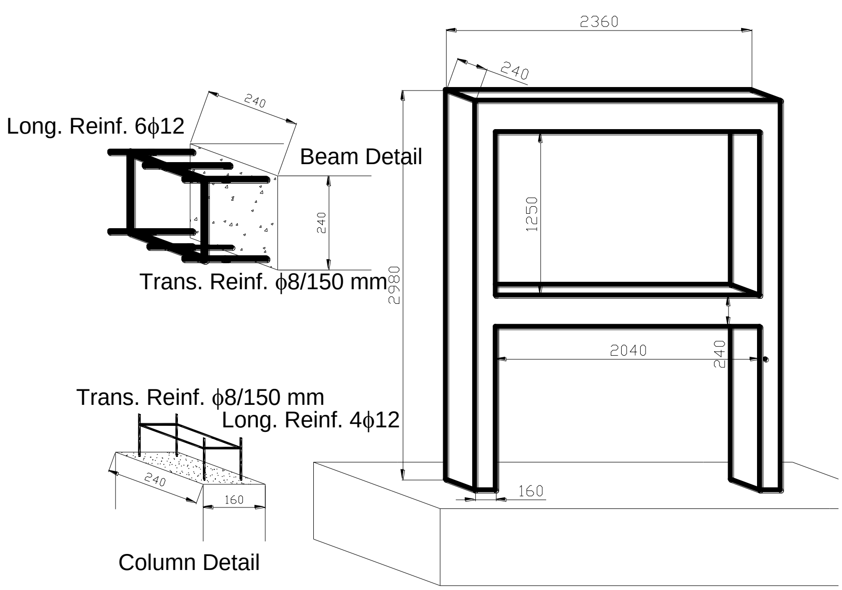


Figure (1): *Dimensions and reinforcement details of the test frames (in mm)*

Test frames possessing commonly observed weaknesses in residential buildings in Turkey. Plain bars were used as longitudinal and transverse reinforcement. Such steel has been used in most of the existing buildings. Transverse reinforcements were spaced with 150 mm intervals. Column ends and joint regions were not sufficiently confined. Insufficient lap splices exist at column and beam ends (Figure 2). Also during design phase of the frames, formation of weak-column, strong-beam connections that are encountered frequently in practice were aimed.

In the experimental program totally six specimens were tested. First two specimens (RFB1 and RISPS) contain no strengthening. Specimen 1 (RFB1) was the bare frame with no infill wall and used as reference specimen. The second specimen (RISPS2) was also reference specimen with ordinary infill wall. The other specimens were strengthened by introducing external mesh reinforcement and plaster over the existing brick infill wall. The mesh reinforcement was consisted of 16mmx16mm square meshes. The diameter of the mesh was ϕ1.1. The yield strength of the mesh reinforcement is 340 MPa and ultimate strength is 420 MPa.

Figure (2) *Reinforcement details of the specimen*

The connection between the existing frame and the infill was achieved by means of steel dowels that were made up of 10 mm diameter bars embedded into columns and beams. These dowels were expected to transfer the shear forces from beam to the infill wall. On the inner faces beams and columns, holes were drilled and cleaned with pressured air. The depth of the holes equals to 10ϕ. The external mesh was applied on the inner faces of the wall panels and epoxy was injected in to holes and dowels were inserted into the holes. Finally plaster prepared according to the mix proportion given in the Turkish Earthquake Code is applied on the surface of the mesh-wall composite (Figure 3). The specimens have the common property of weakly connection between the frames and the infills. Blocks were laid such that their holes were oriented vertically. Special ½ scaled perforated clay bricks were used. For strengthened specimens first dowel holes were drilled and mesh reinforcement placed, finally dowels were anchored. At the last stage plaster was applied on the surface of the wall-mesh interface. The joint mortar, made of cement, lime, and sand in the proportion 1.0:0.65:6.6 was used to construct the brick masonry wall. Frames with low compressive strength were constructed. 15-MPa.

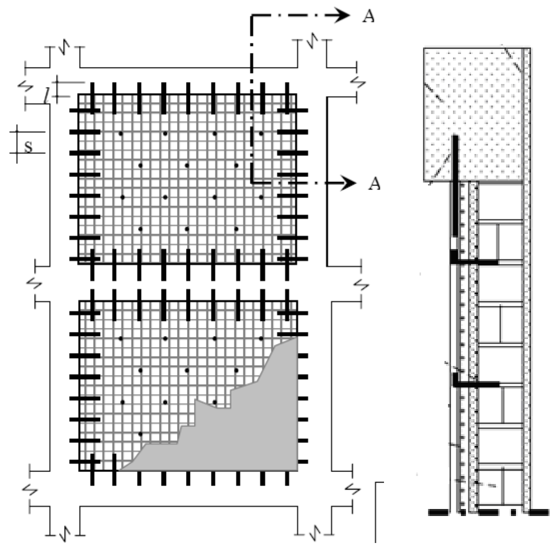


Figure (3) *Plastered wall with welded external mesh and plaster composite (TEC-2007)*

3. Instrumentation and test procedure

The testing system consisted of strong floor, reaction wall, loading equipment, instrumentation, and data acquisition system. The lateral loads were imposed by means of hydraulic actuators placed against a rigid reaction wall. Specimens were tested under cyclic lateral loading applied to both stories at beam levels. A special loading apparatus was used to apply 1/3 of the base shear to the first story and 2/3 of the base shear to the second story. The ratio of the top storey load to the middle storey load was 2. Magnitude of the total force was measured by a load cell with 50 ton compression capacities. The schematic representation of test setup, loading system, and instrumentation is shown in Figure 4.

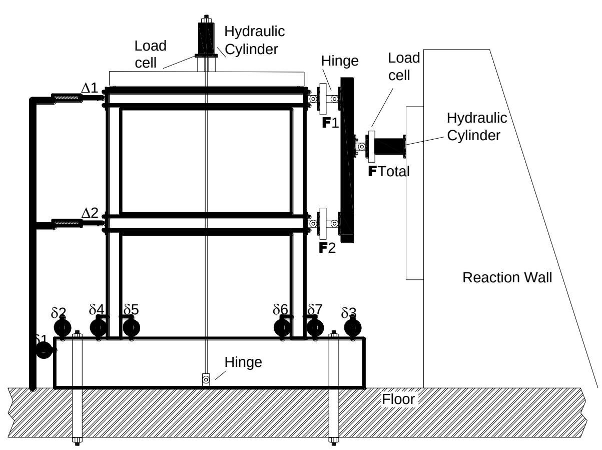


Figure (4) *Test setup, loading system, and instrumentation*

The axial load to simulate a dead load was applied to the specimen columns by two vertical hydraulic jacks. Approximately %15 of the axial load capacity of the columns was applied to the columns top. Reversed cyclic lateral loading scheme is applied in order to represent the earthquake loading. Two categories of loading were considered. First cycle is the load targeted elastic cycle and finalized before the predicted yield load. After yield limit of the specimen, displacements targeted or based cycles were applied.

4. Instrumentation and test procedure

Specimen 1 was the reference specimen and contained no infill. The reinforcement details of the specimens were not in accordance to the Turkish Earthquake Code and a nonductile frame was tried to form. RFB1 was tested to understand the bare frame capacity (Figure 5).

Second specimen (RISPS) tested was the reference specimen with unreinforced infill wall. This specimen contained no strengthening and tested to understand the reference behavior of the infilled original frame. The reinforcement details and the quality of the concrete were same as the RFB1. Special ½ scaled perforated clay bricks were used with ordinary mortar. Bricks were laid such that their holes were parallel to the horizontal plane (Figure 6). This application is common in Turkey for external walls of the framed structures. The infill walls were not constructed on the symmetry axis of the frame for simulating exterior walls of the building.

Figure (5) *Reference empty frame RFB1*

Figure (6) *½ scaled bricks were used with ordinary mortar*

The failure mode of the infill wall was the corner damage and crushing of the wall panel. Bottom storey wall panel damaged more than the upper one. After the infill was crushed at the upper corners due to diagonal compression, the specimen lost its lateral load carrying capacity and thus, failed. The representation of the failure mode of the wall is given in Figure 7.

Figure (7) *Failure modes of the wall portions*

The third specimen, SPS1, was similar to the specimen RISPS2 and strengthening procedure is applied. Wall construction details were same as the RISPS2. After the infill wall was constructed, holes were drilled on the inner faces of the beams and columns. Since the thickness of the columns was higher than the thickness of the wall, there was enough distance on the face of the beams and columns. After the placement of the mesh reinforcement, holes were filled with epoxy and dowels were inserted. Finally plaster was applied over the surface. The thickness of the plaster was 15 mm.

During testing, specimen SPS1 was showed higher initial stiffness than the RFB1 and RISPS2. Also total lateral load carrying capacity of the SPS1 was increased as compared to RFB1 and RISPS2. Several flexural cracks were observed on the beams and columns. But below the first storey beam, premature and sudden failure of the wall-plaster-dowel interface was observed. The plaster cover over the dowels disintegrated and no more shear transfer between beam and the wall become possible. This failure mode (Figure 8) was very sudden and in brittle nature. The full capacity of the mesh-plaster-wall composite couldn't used due to this premature failure. After the failure, the specimen showed similar load-displacement characteristics with the RFB2 specimen. This failure was attributed to inadequate plaster thickness and at the end of the test, it is decided to increase the thickness of the plaster. The failure mode of the specimen at the end of the test is given in Figure 8. This specimen lost 55% of its lateral load carrying capacity immediately after failure of the dowel anchorage with the mesh plaster composite.

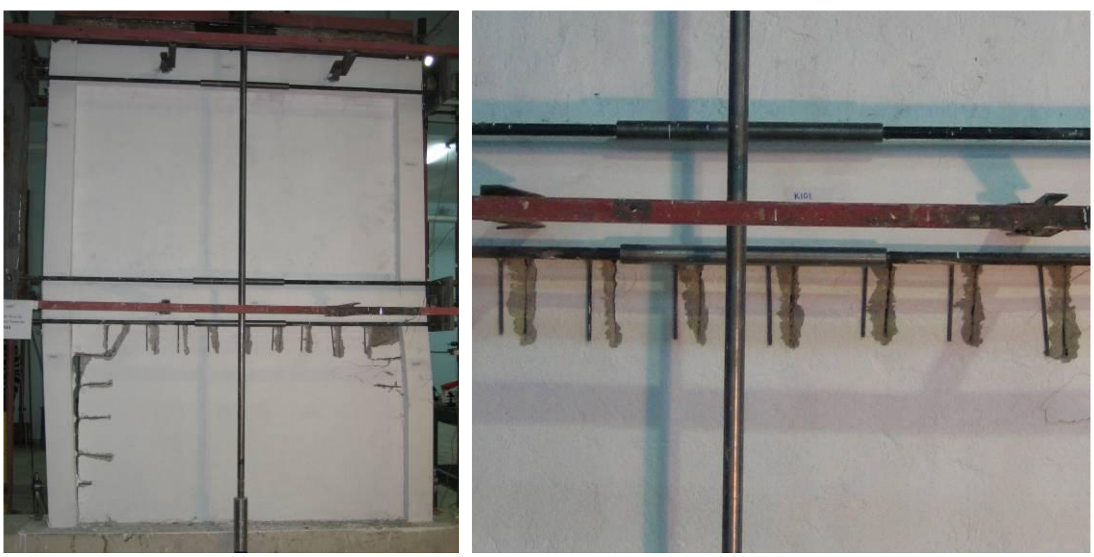


Figure (8) *Failure mode of specimen SP1*

The fourth specimen SP2 was strengthened using the results of the specimen SPS1. The thickness of the plaster was increased and applied as 20 mm. Increase in the plaster thickness in specimen SP2 improved stiffness as compared with Specimen SPS1. This specimen showed higher ultimate load than the specimen SPS1. Again initial flexural cracks were observed on RC members. Specimens SP2, SPS1 showed similar behavior and failure modes. The first cracks over the infill observed on the dowels. A similar but slower type of failure was observed like SPS1. As the applied cycles and displacements increased, disintegration between dowels and plaster become serious. This disintegration dropped the lateral load capacity of the frame (Figure 9).

Figure (9) *Failure mode of the specimen SP2*

For specimen SP3, plaster thickness was chosen as 30 mm and also the strength of the plaster was increased to 30 MPa. Since the dimensions of the mesh were smaller than the dimensions of the brick area, two pieces of mesh were applied over the brick wall. The splice line was on the middle of the beam. Two meshes were spliced 300 mm at the junction point. Flexural cracks initiated and concentrated at column lap splice regions. During the testing, again several cracks were observed on the dowel points but no shear failure was occurred. Instead, the splice of the mesh reinforcement line on the middle was torn. The success of proposed strengthening method mainly depended on the connection provided between the frame and the infill. The load carrying capacity of the specimen dropped after the failure was observed. This type of failure progressed more slowly than the failure observed in specimens SPS1 and SP2. The test photos of the SP3 are given in Figure 10.

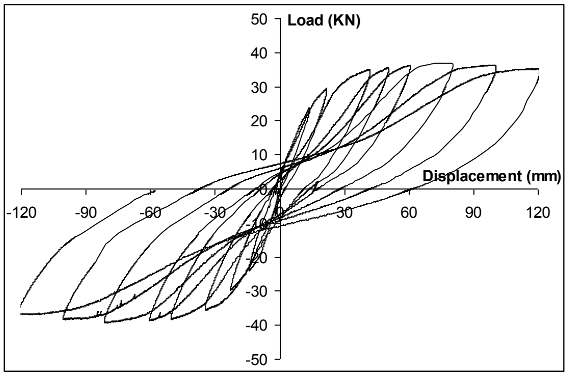
After a splice failure in SP3, and shear failures in SPS1 and SP2, the mesh reinforcement of the SP4 was doubled with same plaster thickness with SP3. Combined type of failure mode in SP4 was observed. Bond deterioration between dowels and the plaster was initiated but not progressed further. Corner crushing of the wall panels were observed. Inclined shear cracks were initiated. Ultimate load capacity of the SP4 was noticeably higher than the other specimens. The cracks over the plastered mesh panels showed a load distribution between the wall and frame system (Figure 11).

Figure (10) *Failure mode of the specimen SP3*

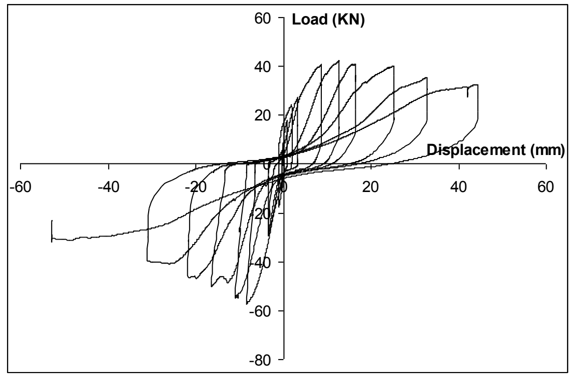
Figure (11) *Failure mode of the specimen SP4*

5. Experimental Results

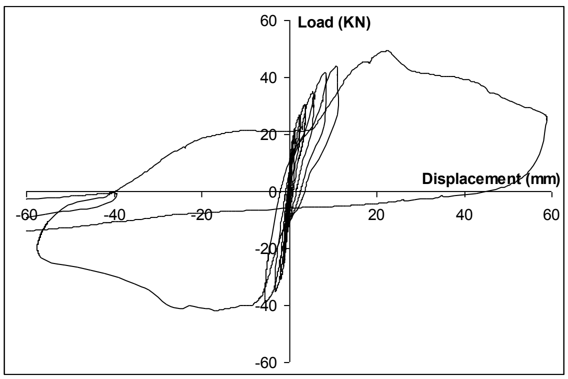
The total load applied- lateral displacement hysteresis curves are represented in Figure 12 for all specimens. In specimen SP2, sudden failure of the dowel-wall interface was clearly observed from the strength drop of load-displacement hysteresis curve in the last cycle. In the last cycle, there is a sudden drop in the load carried by the system and at the same time there is a sudden increase in the lateral displacement. Same type of drop in the lateral load capacity is seen in curves of the SP3 which was failed due to dowel-wall anchorage deterioration too. SPS1 showed inferior behavior among the strengthened specimens.



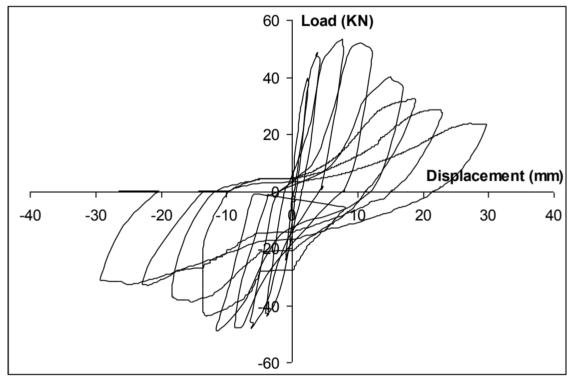
a)RFB1



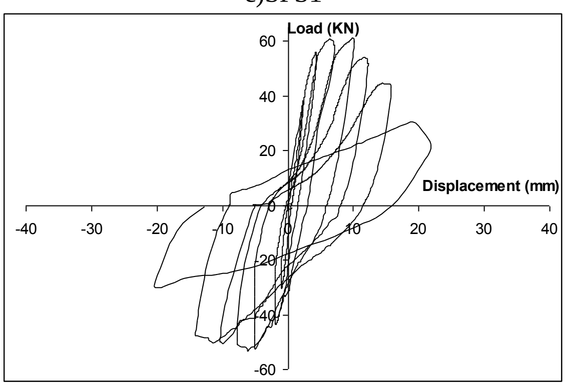
b)RISPS2



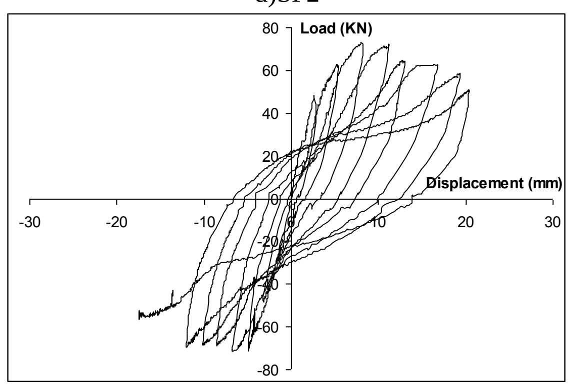
c)SPS1



d)SP2



e)SP3



f)SP4

Figure (12) *Load –displacement hysteretic curves*

To evaluate and compare the lateral strength and the stiffness of the test specimens, envelope curves were constructed. Those envelope curves were obtained by connecting the peak points of the each load cycle. Response envelope curves of the strengthened specimens are given in Figure 13 together with the response envelope curve of the reference bare frame and reference specimen RISPS2 to illustrate the effect of applied rehabilitation techniques on the lateral strength, initial stiffness and the drift ratio on the maximum load. The strength envelopes are used for determining general behaviors and strengths of specimens.

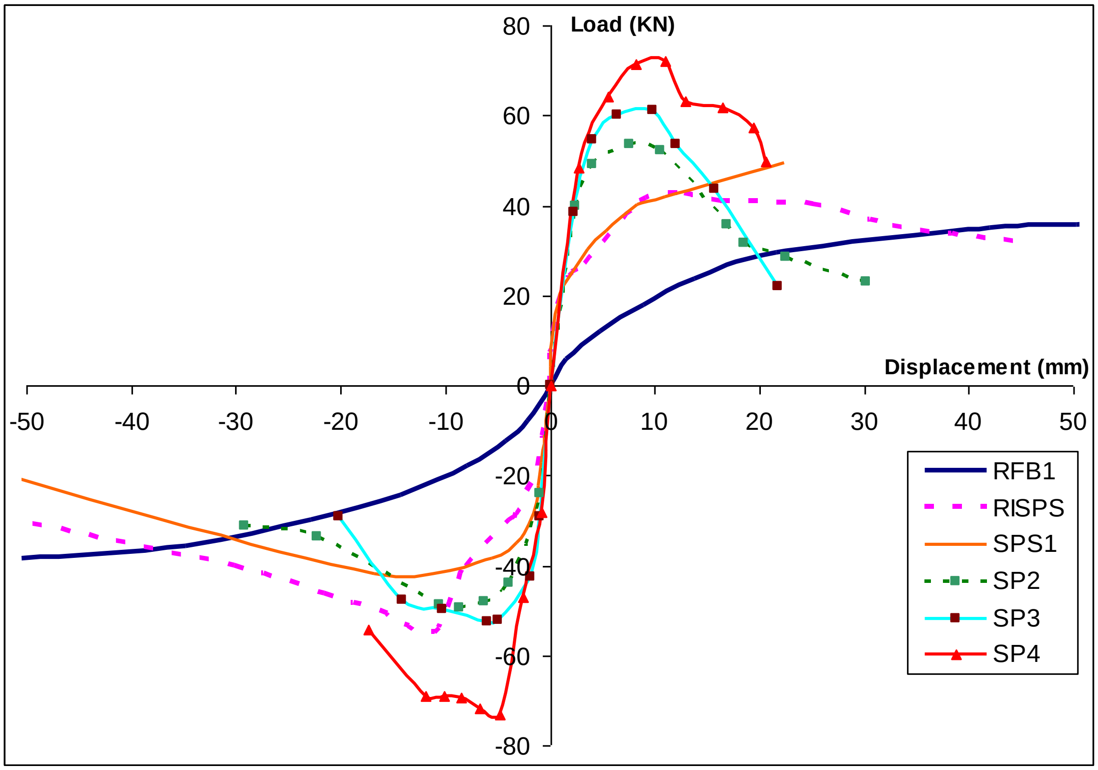


Figure (13) *Envelope curves of the load –displacement curves*

Strength and stiffness of both strengthened frames were significantly higher than those of the bare frame. It is obvious that infilled frame higher initial stiffness than the bare frame but strength loss is observed beyond the peak point. The addition of infill walls increased strength and stiffness of nonductile RC frames, and decreased drift ratios, as expected. Specimen SPS1 and SP2 survived higher lateral loads. The specimen SPS1 approximately followed the infilled specimens (RSPS2) envelope curve and after failure, the load carried by the system was dropped to bare frames level. Specimen SP2 was showed higher performance in terms of lateral load capacity with respect to the SPS1, but sharp decrease in the curve after 15 mm lateral displacement levels is noticeable. Performance of specimen SP3 is superior to SP2. The load capacity is limited due to anchorage loss of the mesh reinforcement and in specimen SP4, the mesh reinforcement was doubled and lap splice of the mesh pieces were increased. Although several cracks were formed on the anchorage dowels and damage or crushing of the corners of the walls were observed, load carried by the system didn’t dropped rapidly and formation of tensile cracks were observed over the strengthened wall panels. The ratio of the ultimate lateral strength of Specimens that were strengthened to that of the reference specimen is ranged between 1,42 and 2.

As expected bare frame displayed lowest initial stiffness value among the others. Inclusion of the infill wall increased the stiffness and strength of the frame and decreased the story drift. Initial stiffness value of the specimen SPS1 is close to RISPS2. SP4 displayed highest stiffness values among the other specimens. Stiffness characteristics of the SP3 are superior to the specimens SP2 values. Stiffness degradation is more pronounced for specimens SP2 and SP3 than SP4. As the cycles were applied and the total displacements were increased, stiffness values were decreased. Increasing the stiffness of the structure may prevent early collapse and reduce interstory drift. High drift levels may cause excessive damage to nonstructural elements [1].

6. Conclussion

The following conclusions and main outcomes of the experimental study can be drawn from tests on nonductile RC frames with and without mesh reinforcement and plaster.

A first aspect to be examined is the behavior of the bare frame compared with the infilled frame case. A comparison can be realized examining the envelope diagrams. The principle difference between the bare frame and frame infilled with unreinforced masonry wall is that the high initial stiffness and high lateral load capacity. Strength, stiffness and energy dissipation capacity of infilled specimen were significantly higher than those for bare frames.

Observing the force-displacement envelopes, panel with external reinforcement collaborates with the frame and it gives non-negligible contribution of strength and stiffness. Panels provide relevant resistance to the lateral loads. Similar results were deduced in the study of Calvi [3]. On the other hand, dowels used as shear keys were debonded at the ultimate load levels of the specimens SPS1. In specimen SP2, the thickness of the plaster is increased and rapid failure of the dowels were delayed but couldn't prevented. The performance of retrofitted frames limited by the premature failure of dowel-plaster-wall interface. As a result, expected performance can not be obtained from strengthening with composite infill walls.

Thickness increase in specimen SP3 showed significant improvements in strength, stiffness and energy dissipation capacity relative to SPS1 and SP2. Results from specimen SP3 test show that the proposed composites with 30 mm plaster thickness application provide more robust connection and can successfully enhance the original structure. But in this case another failure mode was observed and the external mesh reinforcement suffered anchorage problem.

In specimen SP4 where the anchorage length of the external reinforcement was increased, debonding of the shear keys initiated but didn't progress further. No anchorage problems were encountered for external reinforcement. Instead, infill wall joints were crushed at the upper and lower corners of the infill wall. Also cracks were spread over the reinforced wall panels. Specimen SP4 exhibited significantly higher ultimate strength and higher stiffness than the others.

The maximum drift *(Δ*max*)* was approximated as the drift ratio corresponding to the strength deteriorated by 20% of *V*max (0.8 times *V*max) (Han ,2005). Turkish seismic code specifies the interstorey drift limit as 0.35% for the RC framed systems. This value in Eurocode 8 regulations, for brittle nonstructural infills in contact with the RC frame, is taken equal to 0.5% [5]. For specimen RISPS2 and SPS1, maximum drift ratios were 1,99 and 1,31 respectively. For SP2, SP3 and SP4, Eurocode 8 limit didn't exceeded. There was no significant degradation in lateral load carrying capacity for those specimens up to this limit value.

The authors concluded that, when the external mesh reinforcement-plaster composite were connected correctly with the frames as well as infill wall, new lateral load carrying system was generated, the ultimate lateral load carrying capacity was increased and storey drift ratio was reduced significantly. This technique is an economical, efficient and practical solution for the strengthening for buildings with poor seismic performance.

It is beneficial to note that although the elastic modulus of plaster is less than that of concrete, the increase in stiffness and load carrying capacity of frame was significant. The success of the strengthening technique was closely related to the quality of the construction. The success of this technique depends mainly on the successful application of anchorages between the dowels and the infill wall or frame. An important advantage of this technique is that it can be applied without evacuating the building during its application, thus causing minimum disturbance to the occupants.

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