CFRP OVERLAYS IN STRENGTHENING OF FRAMES WITH COLUMN REBAR LAP SPLICE PROBLEM

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Abstract. This study is part of a research program within the framework of NATO Project 977231 "Seismic Assessment and Rehabilitation of Existing Buildings" led by METU. A new seismic retrofitting method by using CFRP cross overlays is experimentally investigated. Five specimens were tested to highlight the effect of brick infill and epoxy bonded CFRP overlays on the strength and behavior of poorly detailed reinforced concrete frames. The main deficiencies of the one-third scale one-bay, two-story frames tested were low concrete strength, insufficient column lap splice length, poor confinement, and inadequate anchorage length of beam bottom reinforcement. In all specimens beams were stronger than columns and no joint shear reinforcement was used.

Keywords: reinforced concrete; rehabilitation; fiber-reinforced polymer; loading; strength

1. Introduction

Observations made after the recent earthquakes revealed that many existing structures located in seismic regions have inadequate lateral strength, ductility and stiffness. Among the other factors, non-ductile frame structures with unreinforced masonry infill have a significant role in contributing to the

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disastrous consequences of the earthquakes. Countries of seismically active regions such as Turkey, Greece, Japan, Italy and Mexico, have suffered extensive damage due to catastrophic effects of recent earthquakes.

Lately, a significant amount of research has been devoted to the study of various strengthening techniques to enhance the seismic performance of the predominant structural system of the region, which is reinforced concrete frames with unreinforced masonry infills. The use of CFRP materials offers important advantages such as ease of application, minimum disturbance to the occupants and savings in construction cost and time in addition to their advanced mechanical properties. The main objective of the study was to understand the performance and failure mechanism of the reinforced concrete frames strengthened with CFRP overlays applied to the masonry infill panels. It is anticipated that the use of FRP on masonry will involve walls resisting in-plane and out-of-plane loads and, possibly, in-fill panels. Indeed, the majority of the work conducted to date has been on the out-of-plane capacity of walls with externally applied FRP. Therefore, it is obvious that the number of experimental and theoretical studies on the relevant subject is very limited.

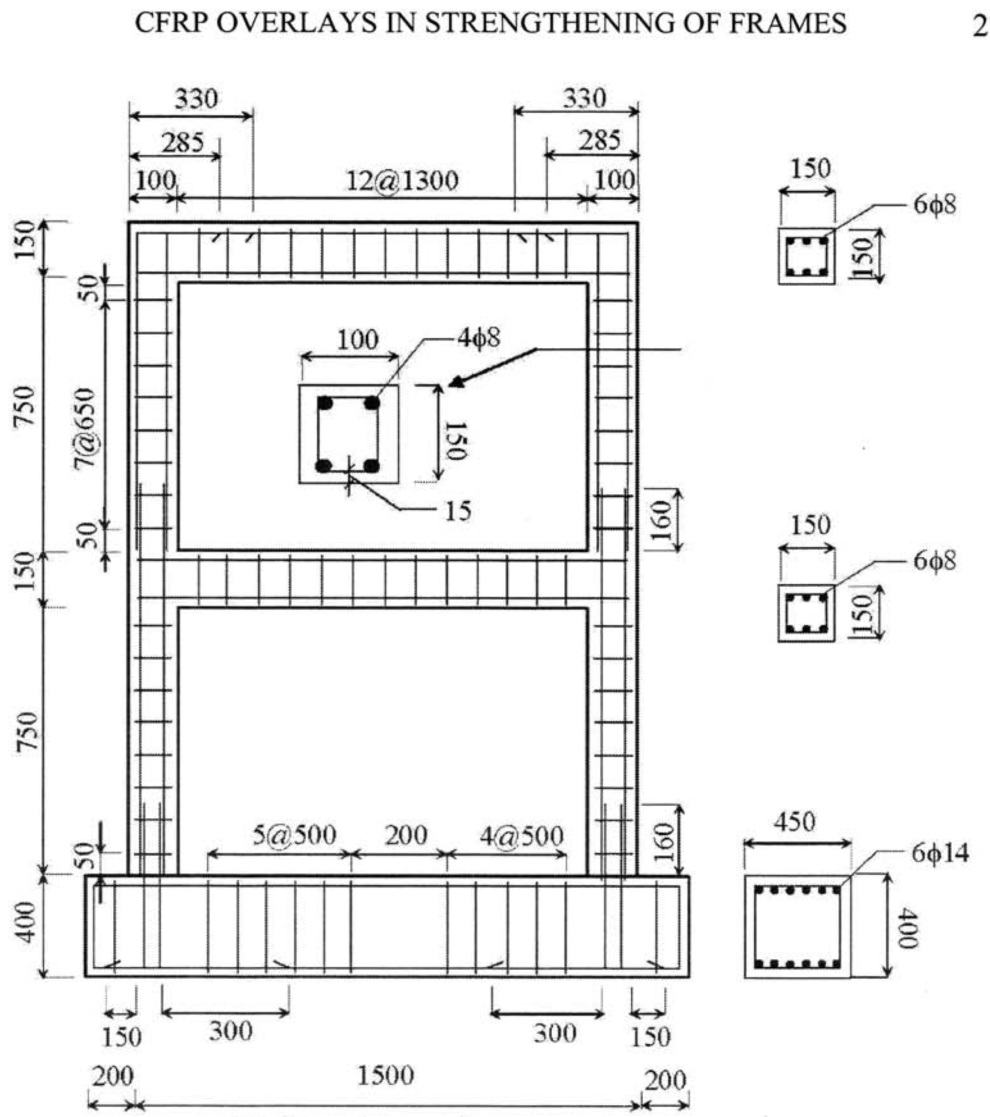
2. Experimental Study

Due to the limitations in testing facilities, five test specimens, namely U1 (bare frame), U2, U3, U4 and U5 (infilled frames), were designed to one-third scale one-bay, two-story frames [1]. Reinforcement detail of the specimens is shown in Figure 1. The properties of the test specimens and materials are summarized in Table 1.

TABLE 1. The properties of the test specimens and materials

Specimen	Type	Long. Reinforcement		Lap Splice Length (mm)	f_c' (MPa)	f_m' (MPa)
		Columns	Beams			
U1	Bare	4-8 mm	6-8 mm	160	15.4	-
U2	Infilled	4-8 mm	6-8 mm	160	14.8	5.5
U3	Infilled	4-8 mm	6-8 mm	160	16.1	5.1
U4	Infilled	4-8 mm	6-8 mm	160	15.3	3.8
U5	Infilled	4-8 mm	6-8 mm	160	14.4	4.7

Material	Type	f_y (MPa)	f_u (MPa)	E (MPa)
Steel	Stirrup	241	423	198,600
	Long.	380	518	194,400
CFRP		N/A	3,500	230,000
Epoxy		N/A	30	3,800



All dimensions are in mm

Figure 1. Reinforcement detail

Lateral loading was applied with a displacement controlled 250 kN capacity hydraulic actuator. For the bare-frame test specimen, the horizontal cyclic loading was applied to the second story beam level only, while the load was divided into two by a steel spreader beam and applied both at the first and second story levels for brick infilled specimens such that two thirds of the applied load goes to the upper story level. Axial load (N/No=0.10) was applied by means of a vertical load distributing beam to the columns evenly. Test set-up can be seen in Figure 2. Loading pattern consisted of two-phase: load control was used till the specimen reached yielding point; and displacement control was used such that the top deflection reached integer multiples of the yield displacement in both directions. Each test continued until the specimen experienced a significant loss of capacity.

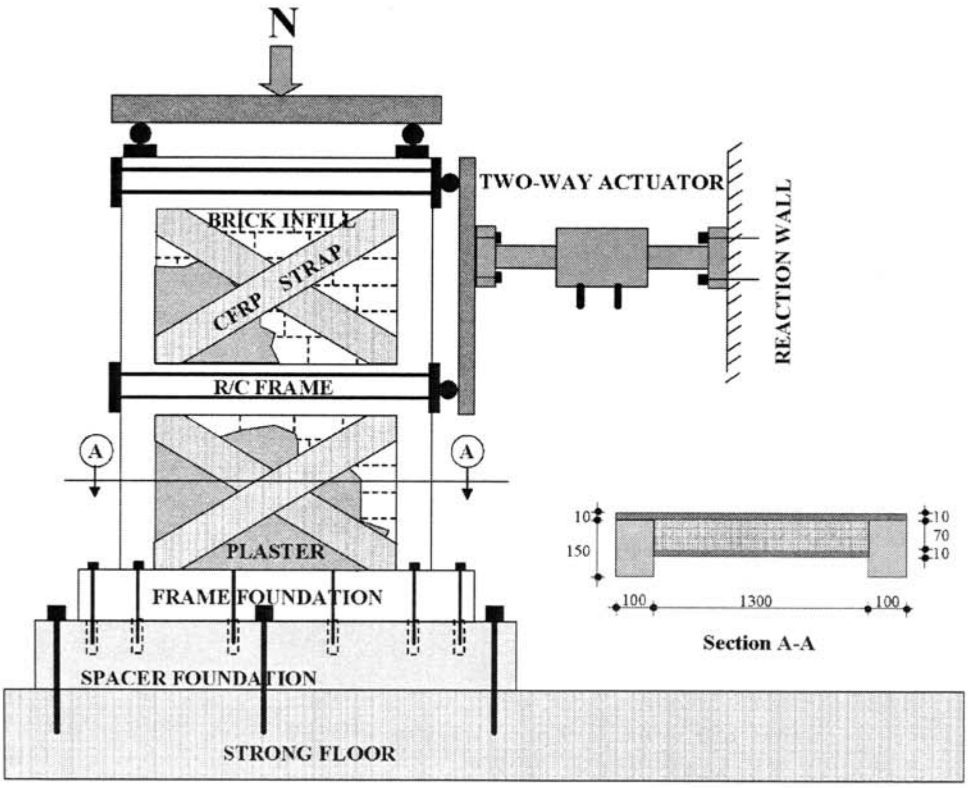


Figure 2. Test set-up

Electronic data acquisition system with control feedback was used to measure the level of applied load, displacements and rotations. In all the specimens, reversed cyclic load level and the frame top displacement were monitored to apply the predetermined loading regime. Curvature measurements on bare frame columns were made to highlight the effect of inadequate lap splice length. Out of plane displacements were recorded both for the bare frame and infilled frame specimens, although the infilled frame ones were restrained against such deformations by means of a steel frame constructed in the test rig. For infilled specimens shear deformations on the brick infill, horizontal base slip, and frame base rocking also measured. The measurements were relative to the frame foundation in all the specimens.

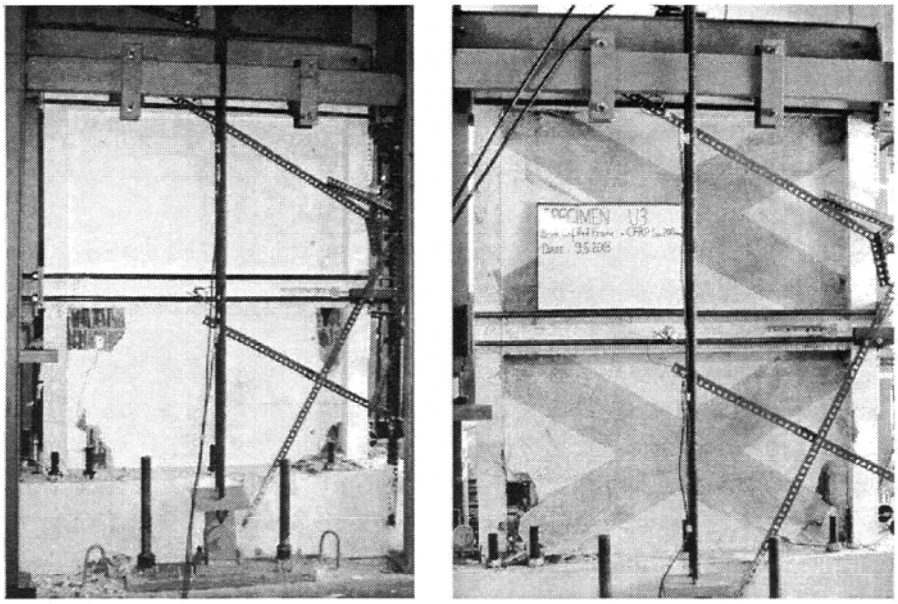
3. Observed Behavior of Test Specimens

Specimen U1: First cracks observed at a load level of 7kN on the base of lower left column. In the 7th cycle (10kN) specimen reached its yielding capacity. After the drift level of 1.65% the lateral load capacity of the specimen stabilized under the increasing lateral displacements. The failure of the system was a typical frame failure. It turned into a mechanism by the formation of plastic hinges in the beam-column joints and in the columns especially at the lap splice regions.

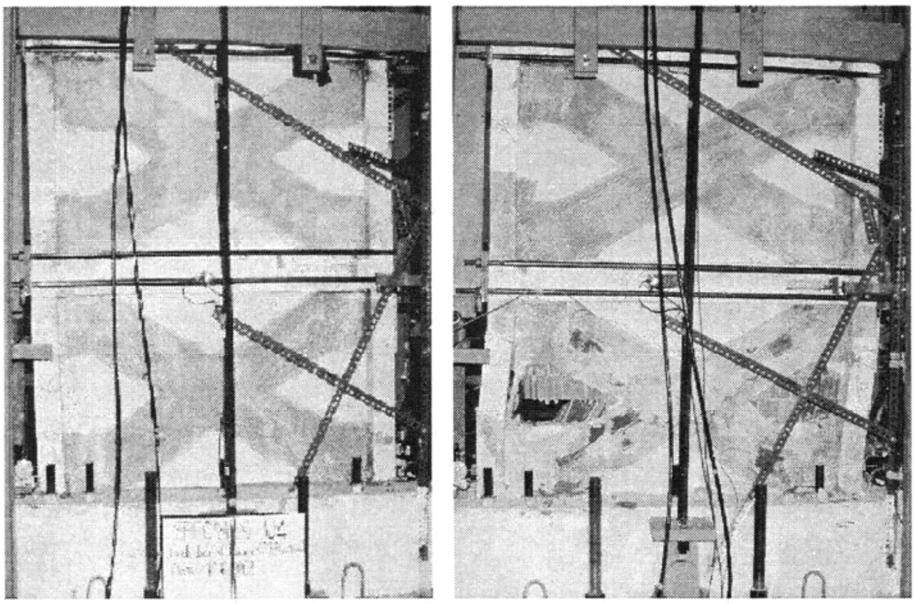
Specimen U2: First cracks observed at a load level of 40kN through the second story brick wall. In the 8th cycle (55kN, 0.14% drift) specimen reached its yielding point. At a drift level of 0.34% sliding was observed between the first story wall panel and beam. After the drift level of 0.55% crack propagation stabilized and separation of the infill panel into four parts completed. The failure mechanism can be identified as a combination of flexure, sliding and crushing of the infill panel at compression regions due to compression strut formation. Damage accumulation and final conditions of the front faces of the infilled specimens can be seen in Figure 3.

Specimen U3: was the first specimen strengthened by means of CFRP overlays applied as cross diagonal strut and placement of anchor dowels into the predetermined locations. The main idea was to investigate the behavior of CFRP sheets and anchor dowels efficiency during the test. Moreover, separation and crushing of the infill from the frame along the compression struts as seen in Specimen-U2 necessitated the using of CFRP sheets as cross-overlays. Close-ups from the CFRP application process and anchor details are shown in Figure 4. First cracks observed at a load level of 35kN in the first and the second story infill panels. In the 12th cycle (75 kN, 0.18% drift) specimen reached its yielding point. At a drift level of 0.31% delamination of CFRP overlay began to form at the frame foundation near both columns and sliding was observed between the beam and first story infill panel. At a drift level of 0.65% separation of the first story panel from the foundation, fracture of CFRP cross overlays and debonding of anchor dowels observed. In the following cycles, at drift level of 0.9%, the cross CFRP overlay sheets buckled and started to debond from the plaster as a result of compression and tension struts. Anchor dowels failed by forming a pull-out cone at the foundation level on both faces.

Specimen U4: Number and depth of the anchor dowels increased. In addition; rectangular CFRP flag sheets applied to each panel corner to prevent the crushing of brick due to the compression strut, additional anchor dowels were aligned in the same direction with cross-overlays. First cracks observed at a load level of 55kN on the first story left columns just above the rectangular CFRP flag. In the 13th cycle (95kN, 0.2% drift) specimen reached its yielding point. At a drift level of 0.34% pre-formed cracks especially located on the bottom of the columns widened suddenly. Columns and the frame foundation separated completely. At further drift levels separation of frame base from foundation and rocking was more pronounced due to complete bond loss of anchor dowels and excessive slip deformation on the columns. Till the end of the test, the specimen remained intact without any crushing of brick infill corner joints and delamination of CFRP from the concrete cover did not appear. Moreover no significant buckling or rupture of CFRP overlay was observed. However, it was revealed that depth of the anchor dowels was not sufficient. The problem of lap-splice in columns governs the capacity and post-failure behavior.



Specimen U2 Specimen U3



Specimen U4 Specimen U5

Figure 3. Damage accumulation

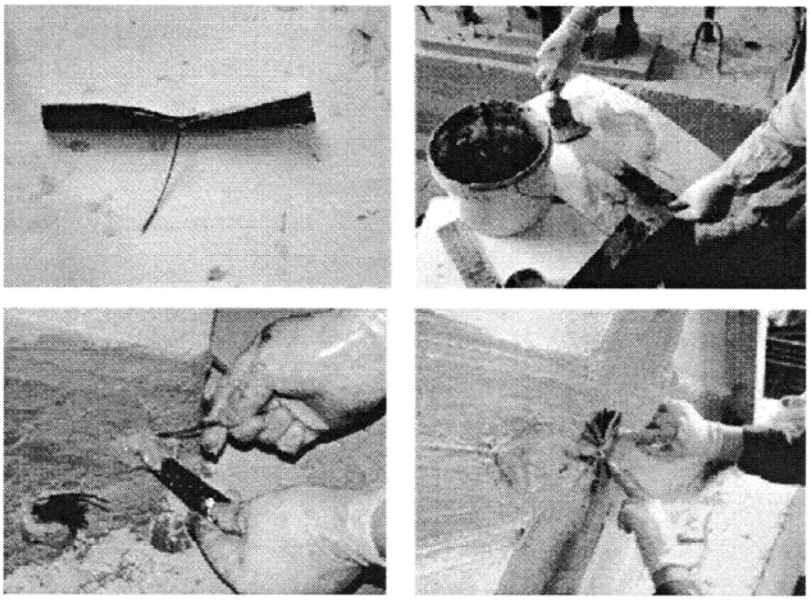


Figure 4. CFRP anchor application

Specimen U4: The number and depth of the anchor dowels were increased. In addition; rectangular CFRP flag sheets were applied to each panel corner to prevent the crushing of brick due to the compression strut, additional anchor dowels were aligned in the same direction with cross-overlays. First cracks observed at a load level of 55kN on the first story left columns just above the rectangular CFRP flag. In the 13th cycle (95kN, 0.2% drift) specimen reached its yielding point. At a drift level of 0.34% pre-formed cracks especially located on the bottom of the columns widened suddenly. Columns and the frame foundation separated completely. At further drift levels separation of frame base from foundation and rocking was more pronounced due to complete bond loss of anchor dowels and excessive slip deformation on the columns. Till the end of the test, specimen remained intact without any crushing of brick infill corner joints and delamination of CFRP from the concrete cover did not appear. Moreover no significant buckling or rupture of CFRP overlay was observed. However, it was revealed that depth of the anchor dowels was not sufficient. The problem of lap-splice in columns governs the capacity and post-failure behavior.

Specimen U5: The strengthening process for Specimen U5 consisted of two phases. First phase was similar to that of U4 except the increment in the depth of foundation level anchorage length up to 12cm. Extra anchor dowels at foundation level with increased anchoring depth together with continuity CFRP sheets along the column splice regions were used. To satisfy the required longitudinal reinforcement at foundation and 1st story level additional CRFP sheets were bonded on the exterior faces of the columns. Afterwards, by wrapping around each column with one layer of CFRP sheet strengthening was finished. First cracks observed at a load level of 55 kN on the left column at the intersection region of the CFRP column wrap. In the 16th cycle at a load level of 95 kN debonding and peeling off was suddenly occurred on the cross overlay CFRP sheets and boundary separation between the columns and the brick infill wall transpired. In the 17th cycle (115 kN) specimen reached its yielding point. After the drift level of 1.39% sudden drop in load capacity observed due to the complete failure of CFRP overlay sheets by means of rupture through the sliding shear plane along the bed joints which is 300 mm above the foundation.

4. Discussion of Test Results

Response envelope curves are developed by connecting the peak values of each cycle for all specimens (Figure 5). Load bearing capacities of all strengthened frames tested are significantly higher than that of the bare frame (Sp-U1) and the unstrengthened infilled specimen (Sp-U2). Although there was a significant strength enhancement in Sp-U5 (1.94 times that of Sp-U2), the enhancement in displacement capacity was more pronounced (5.3 times that of Sp-U2).

Figure 5. Response envelope of specimens

Moreover, the tangent slopes of the load-displacement curves which are called "tangent stiffness" were calculated for each specimen. These representative slopes referred to each forward and backward cycle are all calculated from the experimental load-displacement curves. The degradation of normalized tangent slopes for the forward and backward cycles with corresponding specific roof story drift ratio are given in Figure 6. The drift ratio exceeds 2 percent for bare frames and 0.5 percent for infilled frames, and the amount of stiffness degradation was more than 90 percent for almost all specimens beyond a drift level of 1 percent.

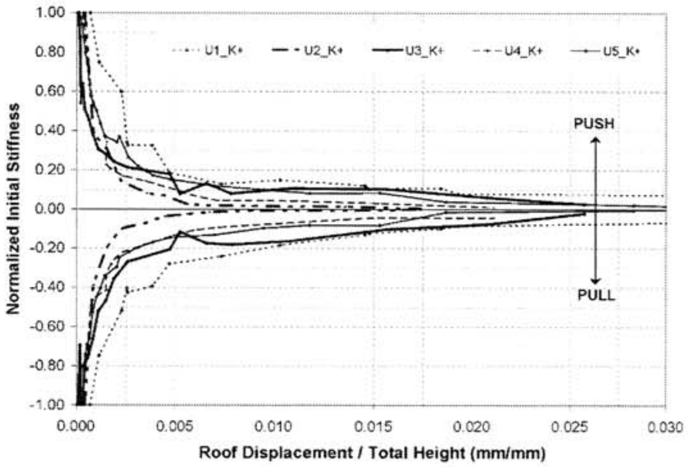


Figure 6. Variation of initial stiffness for each forward and backward cycle

The degree of closing of the existing cracks when the load is reversed is reflected in the load displacement curves with an increased residual deflection. Variation of residual displacement ratio with increasing drift levels is shown in Figure 7.

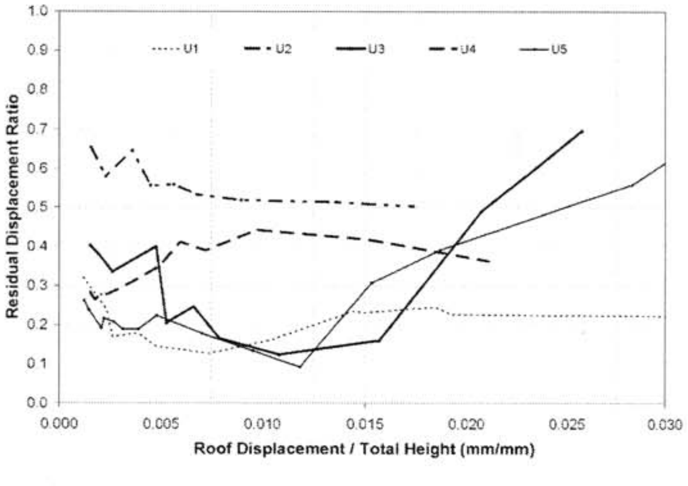


Figure 7. Variation of residual displacement ratio

It is obvious that the capability of a structure to dissipate energy which is defined as the area enclosed by the experimental load-displacement hysteresis loops has a strong influence on its response to an earthquake loading. All specimens except bare frame (Sp-U1) dissipated almost the same amount of energy up to the 0.5% roof drift ratio. Sp-U5 exhibited an increase of 30% in maximum energy and a 20% increase in strength when compared to precedent strengthened specimen, Sp-U4. At 2% drift level, Sp-U5 dissipated 1.5 times more energy than the specimens U3 and U4, while it was 4.5 times greater than the Specimen-U1.

5. Conclusions

The proposed X-overlay CFRP reinforcement scheme with flag sheets and special anchorage details resulted in a significant enhancement in the response of the brick infilled RC frame specimens under reversed cyclic loading. The strengthened specimens yielded a gradual and prolonged failure, a higher base shear, more energy dissipation and apparent post peak strength. However, stiffness enhancement of the specimens was critically low. The interstory drift limit values which are the constraints for rehabilitation of the existing structures should be revised. What is critical here is the reliance on a retrofit analysis and design which limits the story drift to an amount which would prevent any major degradation of the masonry. Test results revealed that an interstory drift level of 0.35% to 0.50% may be a limiting value preventing the CFRP modified masonry from degradation.

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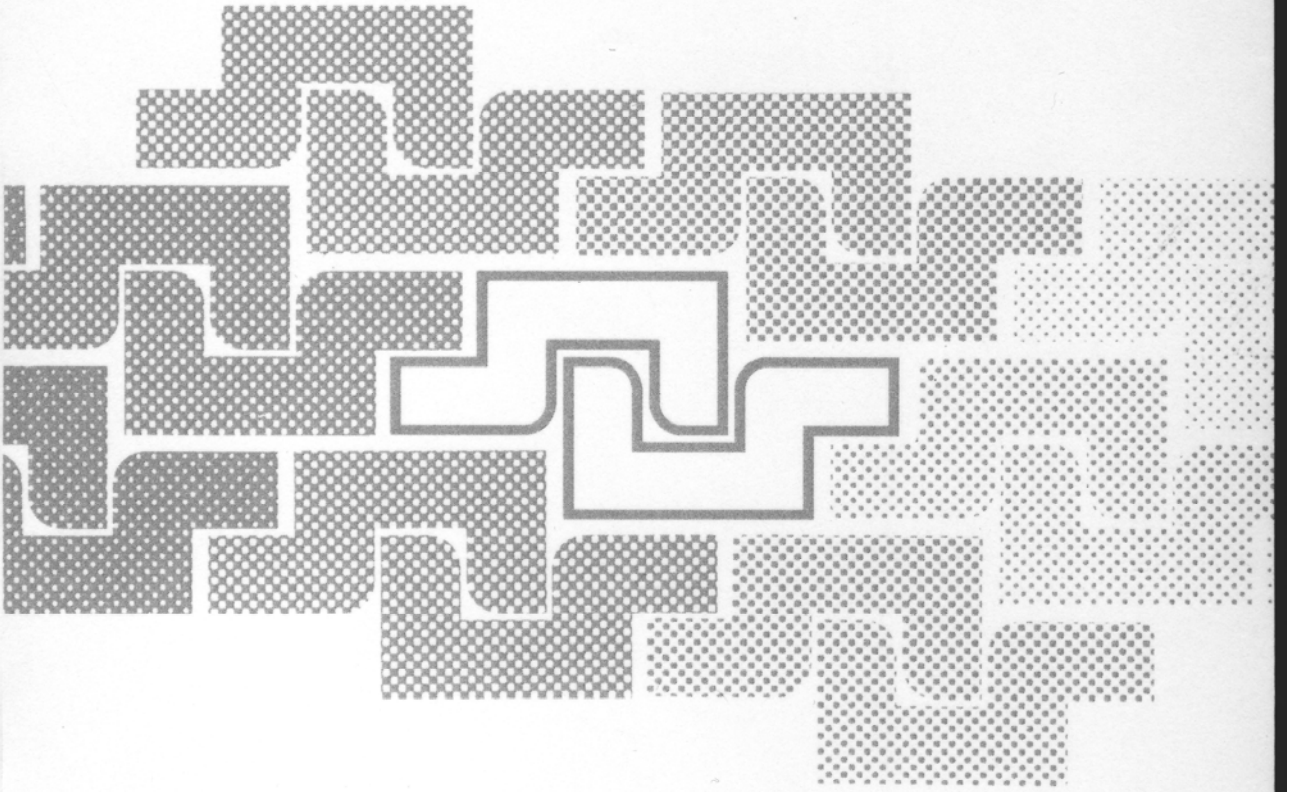

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