STUDY OF THE ANCHORAGE OF CARBON FIBER REINFORCING PLASTICS (CFRP) UTILIZED TO UPGRADE THE FLEXURAL CAPACITY OF VERTICAL R/C MEMBERS

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ABSTRACT :

The upgrading of the flexural capacity of reinforced concrete (R/C) vertical members with externally applied CFRP layers as means of tensile reinforcement is investigated. The specimens were designed that the flexural limit state would prevail in the form of a plastic hinge region near their joint with the foundation. They were subjected to simultaneous constant vertical load and horizontal cyclic displacements. This was applied prior to the application of CFRP layers and was repeated with CFRP layers attached to the damaged specimens. The upgrading of the flexural capacity in terms of ultimate overturning moment is presented and discussed. A critical point is the effective anchoring of the CFRP sheets for the transfer of tensile forces to the foundation. Three different anchoring arrangements are applied sequentially to specimens that have been subjected to a damaging loading process prior to their repair. The anchoring schemes were based on observations and numerical simulation processes aimed to optimize the behavior. After virgin specimens developed the expected flexural plastic hinge three different repair schemes were tried. These repair schemes introduced improvements to the CFRP bonding and improvements to the anchoring arrangements of the CFRP to the foundation. The improvement is judged on the basis of the upgrading of the flexural capacity and on the developing failure mode. The final repair scheme is more practical and was successful in mobilizing the available capacity of the CFRP layers; it resulted in approximately 100% increase in the flexural capacity when compared to the virgin specimen without CFRP layers.

KEYWORDS: Anchoring, CFRP-layers, Tests, flexural-behaviour

1. INTRODUCTION

The upgrading of the flexural capacity of reinforced concrete (R/C) vertical members with externally applied CFRP layers as means of tensile reinforcement is investigated here (fig. 1 and [5]). The CFRP layers are applied at the two opposite sides of R/C specimens which were constructed for this purpose (figures 2a, 2b). They were designed with such longitudinal and transverse reinforcements shown in figure 2b that the flexural limit state would prevail. The specimens were tested to develop the ultimate flexural behavior with the corresponding damaged region concentrated near their joint with the foundation. These specimens had the foundation block fixed at the strong reaction frame of the laboratory of Strength of Materials and Structures of the University of Thessaloniki and were subjected to simultaneous constant vertical load as well as horizontal cyclic imposed displacements approximating thus the seismic actions. This loading sequence was applied prior to the application of any CFRP layers and was repeated again after these CFRP layers were attached to the damaged specimens. The observed upgrading of the flexural capacity in terms of ultimate overturning moment is presented and discussed.

2. THE INITIAL SPECIMEN PIER A AND ITS OBSERVED BEHAVIOR

2.1. The virgin beam specimen

This specimen is shown in figure 2a with a rectangular cross-section of 200 mm x 500 mm and height h = 1815mm (from its top to the upper surface of its foundation). 8Φ6 was the longitudinal reinforcement and Φ6/100 closed stirrups the transverse reinforcement [1]. The detailing of the cross-section is shown in figure 2b. The selected longitudinal and transverse reinforcement together with the loading arrangement, will cause the behavior of this virgin specimen to be dominated by the flexural rather than the shear mode of failure. More details are given in references [1] and [3].

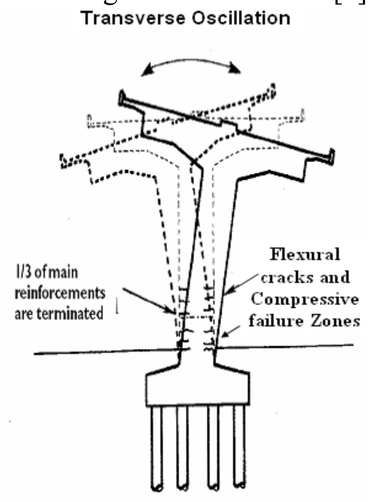


Figure 1. Flexural Damage

Figure 2a. Pier A

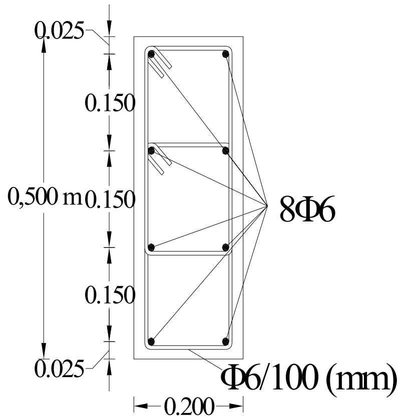


Figure 2b. Cross-section and reinforcing details of Pier A

2.2. The Loading sequence

The foundation of the specimen was anchored at the strong floor of a reaction frame. The specimen was then subjected to a simultaneous constant vertical load and a cyclic horizontal displacement with increasing amplitude in time, utilizing servo-electronically-controlled dynamic actuators. The frequency of this cyclic displacement was in some tests 0.1Hz whereas in other selected tests it became 1.0Hz. The vertical load was kept constant at 95KN. The horizontal imposed cyclic displacement was applied in 13 groups of continuously increasing amplitude. Each group included 3 full cycles of constant amplitude. This time history of the imposed displacement is depicted in figure 3.

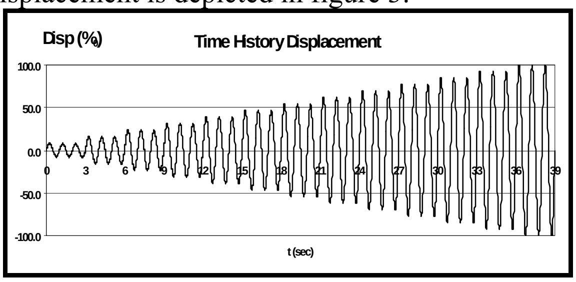
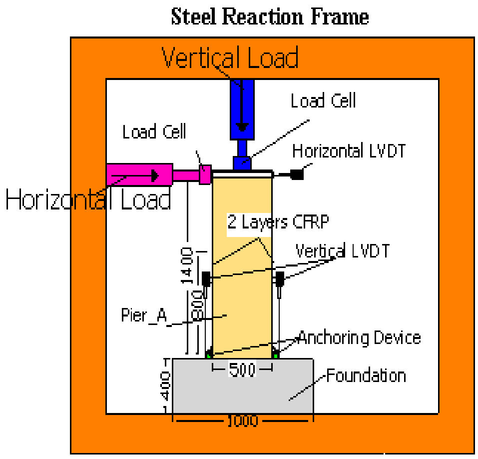


Figure 3. Imposed horizontal displacement

The amplitude in this picture is non-dimensional and is given as a percentage of the maximum final maximum amplitude of this cyclic loading. In the experimental sequence the maximum displacement horizontal amplitude was initially relatively small (2mm); as testing progressed, in subsequent cyclic loading sequences it reached values of 20mm to 25mm. The imposed displacements were measured at the location of the horizontal actuator which was placed at a height of 1400mm from the top of the foundation (figure 4).

Figures 4 and 5 depict this experimental setup. As can be seen the specimen was placed in the strong reaction frame, having its foundation block, with dimensions in plan 1000mm by 1000mm and 300mm height, fully anchored to the strong floor. The horizontal and vertical actuators, as part of this strong reaction frame, applied the loading sequence described above. Instrumentation was provided in order to measure the variation of the applied horizontal and vertical loads as well as the most important aspects of the displacement field that resulted from the application of these loads to the specimen. The horizontal displacements of the specimens at the top were monitored as well as the displacements of the specimen at the region near the foundation block in order to identify the flexural, and shear deformations as well as the plastic hinge behavior at this part of the specimen. In figure 4 the two vertical sides of the specimen where the Carbon Fiber Reinforcing Plastic (CFRP) layers were attached are indicated together with the region where the anchoring arrangements were placed as part of the current investigation. These CFRP layers were placed at these locations after the virgin specimen was damaged from the applied loading sequence, as will be explained in the following sections.



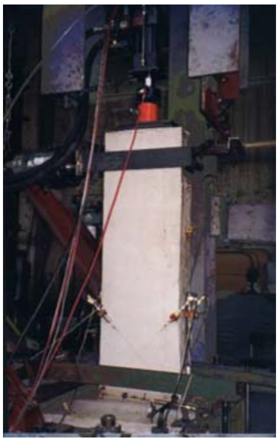


Figure 4. Experimental set-up **Figure 5.** Pier A placed at the strong reaction frame

2.3. The behaviour of Pier A

The yield stress of the longitudinal reinforcements was equal to 344.8Mpa whereas the concrete strength was equal to 21.2Mpa. Based on these mechanical characteristics and the cross-section reinforcing detailing, predictions of the limit-state flexural behavior for this virgin specimen (without CFRP layers) were obtained in terms of the M-N interaction diagrams.

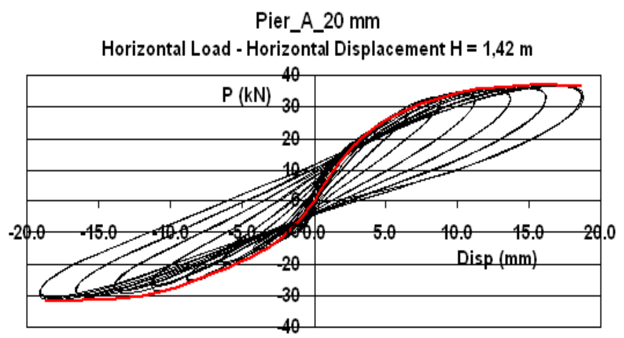


Figure 6a. The measured flexural response of Pier A in terms of horizontal load - horizontal Displacement

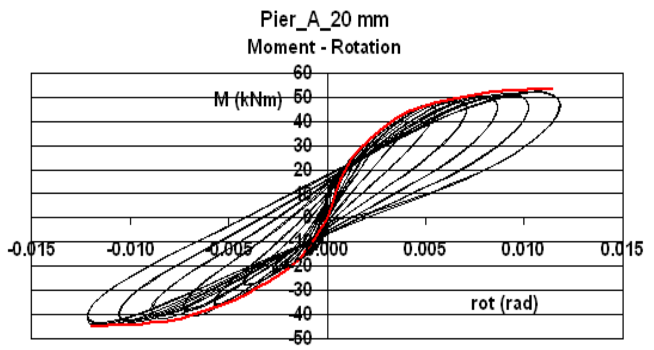


Figure 6b. The measured flexural response of Pier A in terms of bending moment - plastic rotation.

The measured flexural behavior of Pier A is depicted in figures 6a and 6b. Figure 6a shows the observed cyclic response in terms of applied horizontal load and the corresponding measured horizontal displacement. Figure 6b presents the variation of the resulting bending moment at the cross-section of the specimen where the development of flexural cracks took place against the rotation of the same cross section, as measured by displacement transducers that were placed at the two sides of the pier monitoring the relative vertical displacement between the upper part of the specimen and its foundation block. Additional instrumentation was provided to monitor the rocking or the sliding of the foundation block itself, which proved to be non-significant. The red line in these plots represents the corresponding envelope curve.

3. REPAIRED SPECIMEN Rep-1 PIER A AND OBSERVED BEHAVIOUR

The damaged Pier A was repaired in a way depicted by figure 7. The resulting specimen is designated as Rep-1

Pier A. Two layers of CFRP were attached at each vertical side of the pier's cross-section. This attachment extended to a height of 1100mm from the foundation surface as well as at the top surface of the foundation block depicted in figure 7. Moreover, in order to increase the bond strength between the CFRP layers and the top surface of the foundation block two double **T** steel sections were placed at these locations as depicted in figure 7. A force normal to the bond surface at this location was applied by bolting these double **T** steel sections to the foundation block utilizing pre-stressing rods.

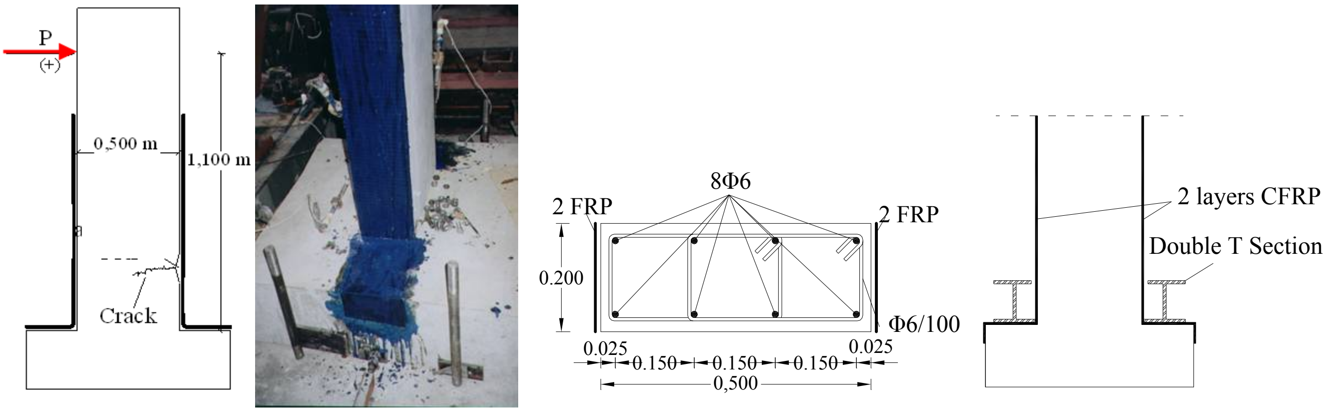


Figure 7. Details for specimen Rep-1 Pier A

3.1. Observed Behavior of Specimen Rep-1 Pier A

The loading sequence, described in section 2, was applied to this repaired specimen. During increasing of the imposed horizontal displacement the detaching of the CFRP layer at the right side of the pier occurred. The obtained flexural behavior is depicted in figure 8 in terms of applied horizontal load against the imposed horizontal displacement at the top of the pier. If this behavior is compared with the corresponding behavior of the virgin specimen Pier A, a modest increase in its bearing capacity of approximately 20% can be observed as a result of the applied CFRP repair scheme, despite the detaching of the CFRP layers. The red line in this figure represents the corresponding envelope curve.

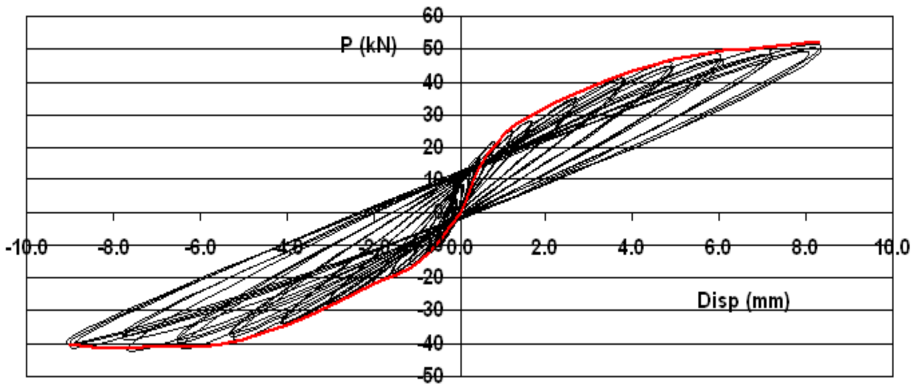


Figure 8. The measured flexural response of Rep-1 Pier A in terms of Horiz. load – Horiz. Displacement.

4. REPAIRED SPECIMEN Rep-2 PIER A AND OBSERVED BEHAVIOUR

The damaged Rep-1 Pier A was repaired again in a way which is shown in figures 9a,b. The CFRP layers that were separated from the concrete at the right side of Rep-1 Pier A was reattached, apart from the appropriate resin, with additional 2mm diameter small bolts having 35mm length; these bolts were spaced at regular 50mm intervals along all the height of the CFRP layer at both sides. Moreover, the edge of the double **T** steel section neighbouring the location of the CFRP layer at the pier-foundation joint was machined to form a curvature so that it provided a relatively uniform contact between the steel section and CFRP layers at this location. The locations of the bolts were first marked and drilled and then the bolts were applied including the corresponding plastic anchoring inserts. The specimen repaired in this way is designated as Rep-2 Pier A.

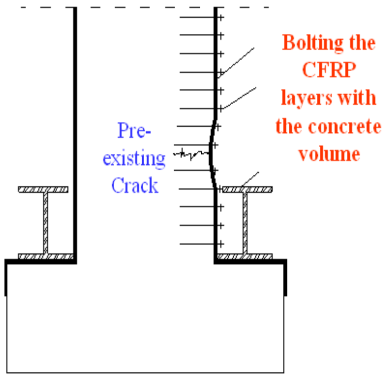


Figure 9a. The repair of specimen Rep-1 Pier A **Figure 9b.** The repair of specimen Rep-1 Pier A

4.1. Observed Behavior of Specimen Rep-2 Pier A

The loading sequence, described in section 2, was also applied for this repaired specimen. During the increasing of the imposed horizontal displacement the fracture of the CFRP layers at the right side of the pier occurred as depicted in figure 10b. This fracture occurred at the location where the pier joins the foundation block. The obtained flexural behavior is depicted in figure 10a in terms of applied horizontal load against the imposed horizontal displacement at the top of the pier. The plastic hinge, which was formed during testing specimen Rep-1 was not repaired in any other way, but with the means described in section 4. The fracture of the CFRP layer depicted in figure 10b took place at the same cross section. The bending moment capacity remains approximately at the same levels, as deduced from the variation of the horizontal load (figures 10a and 11).

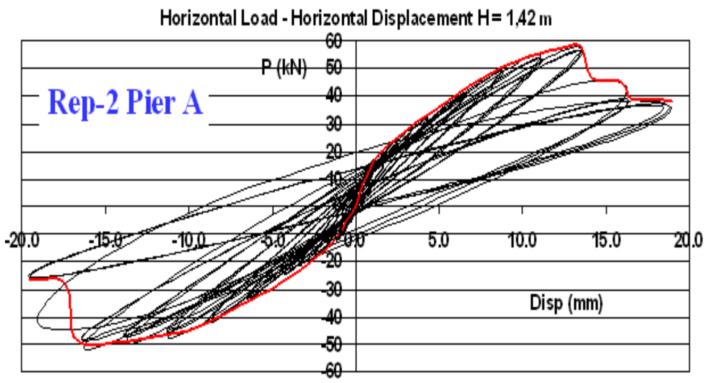


Figure 10a. The measured flexural response of Rep-2 Pier A in terms of horizontal load - horizontal Displacement.

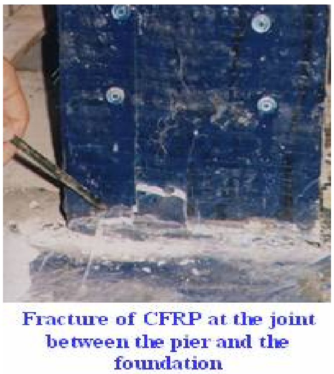


Figure 10b. Fracture of CFRP for specimen Rep-2 Pier A

The effectiveness of the applied repair schemes for specimens Rep-1 and Rep-2 can be seen in figure 11 in terms of envelope curves. The comparison is made in terms of horizontal load – horizontal displacement. As it can be seen, the effectiveness of the CFRP layers is inhibited by the detaching of the CFRP layers; thus although a considerable increase is achieved in the bearing capacity, this is not sustained in terms of displacement because of the premature detaching of the CFRP. The improvement of the bonding with the use of the employed bolting scheme for Rep-2 resulted in an increase of the bearing capacity both in terms of load and displacement and resulted in the fracture of the CFRP.
From figure 12 the effectiveness of the repair scheme utilized in specimen Rep-2 Pier A can be deduced compared with the virgin specimen Pier A in terms of bending moment - plastic hinge rotation. The achieved increase in bending moment is almost 50% and the flexural behavior in terms of rotation is satisfactory up to the fracture of the CFRP layer at the joint between the pier and the foundation.

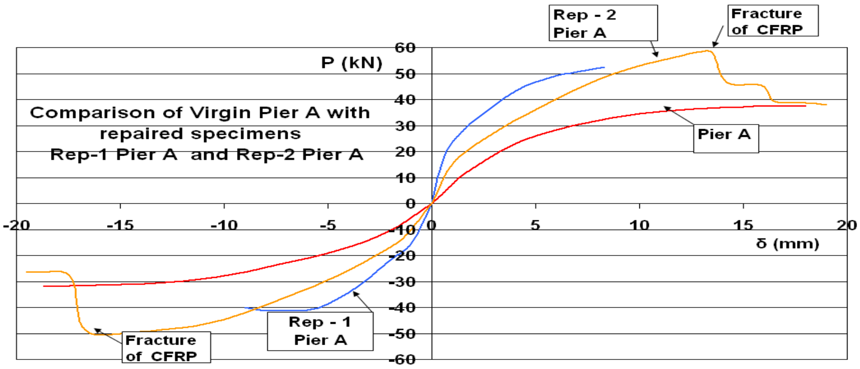


Figure 11. Comparison of flexural response of repaired Rep-2 Pier A with repaired specimen Rep-1 Pier A and virgin specimen Pier A in terms of Horizontal load – Horizontal displacements.

Comparing the maximum value of the bending moment (83KNm) that was resisted by specimen Rep-2 Pier A with the one predicted by numerical simulation (130KNm), as an ultimate bending moment that the cross-section reinforced by the applied CFRP layers can ideally resist, it can be concluded that the fracture of the CFRP did not allow this ideally maximum bending moment value to be reached.

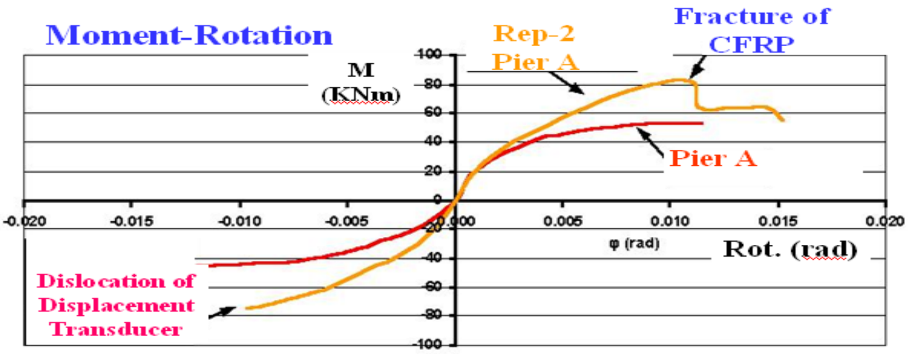


Figure 12. Comparison of flexural response of repaired Rep-2 Pier A with virgin specimen Pier A

One reason for this is the way the anchoring of the CFRP layers at the foundation block is achieved with the utilization of the double **T** steel sections described before. Despite the machining of the edge of these double **T** steel sections the development of high stress levels concentrated at the CFRP layers at these locations is the cause of the observed CFRP fracture. Moreover, such an anchoring scheme is quite impractical for prototype conditions. For these reasons a different anchoring scheme was investigated in order to address both these shortcomings that were found to be critical in the repair schemes investigated so far. This is presented in a summary form in the next section.

5. REPAIRED SPECIMEN Rep-3 PIER A AND OBSERVED BEHAVIOUR

Figure 13a depicts the outline of this anchoring scheme and figure 13b depicts the application of this anchoring scheme for repair specimen Rep-3 Pier A, whereby the CFRP layers are folded around a cylinder that is anchored to the foundation. Moreover, in order to avoid the separation (detachment) of the CFRP layers from the sides of the specimen, as observed in specimen Rep-1, the bolting scheme that was used in specimen Rep-3 was further improved by using bolts and washers of larger size. In addition, to avoid the development of shear failure at the bottom part of the pier, three horizontal CFRP closed hoops were attached in this region of the specimen (figures 13c,d and [4]).

5.1. Observed Behavior of Specimen Rep-3 Pier A

The loading sequence, described in section 2, was also applied for this repaired specimen. During increasing of the imposed horizontal displacement the partial fracture of the CFRP layer at the right side of the pier occurred.

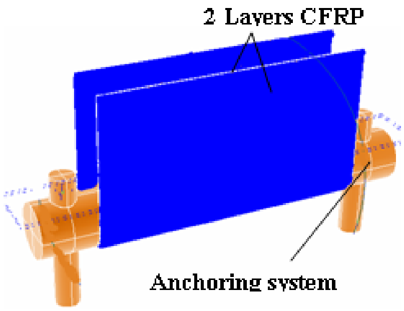


Figure 13a. New anchoring device

Figure 13b. New anchoring device

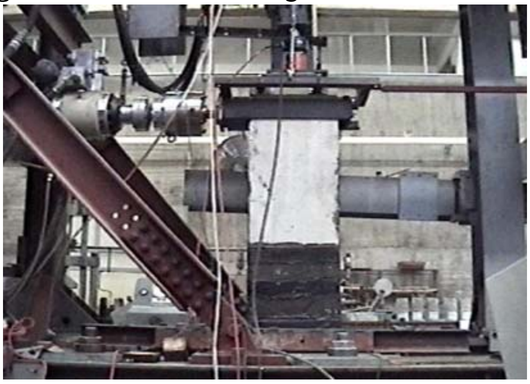


Figure 13c. Specimen Rep-3 Pier A

Figure 13d. Specimen Rep-3 Pier A

This fracture occurred at the location where the CFRP layers are folded around the cylindrical part of the anchoring device. In figures 14a and 14b the measured flexural behavior in terms of horizontal load-horizontal displacement and bending moment-rotation envelope curve diagrams for repaired specimen Rep-1, Rep-2 and Rep-3 is compared with the corresponding flexural behavior of the virgin specimen Pier A. The following observations can be made on the basis of these diagrams.

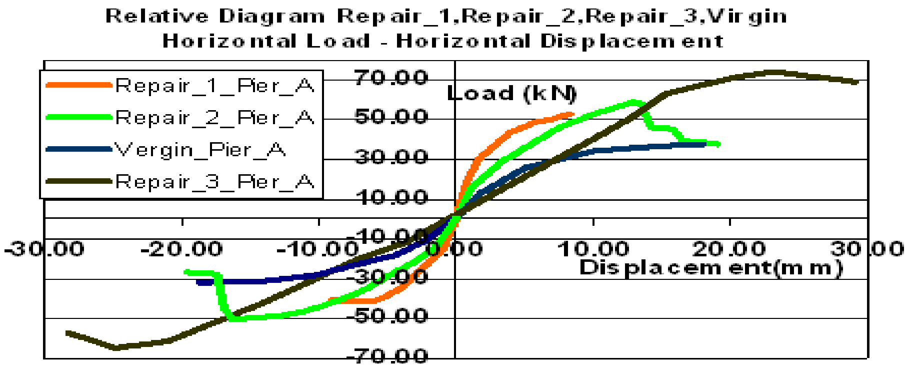


Figure 17a. Flexural response of repaired specimens Rep-3, Rep-2, Rep-1 and virgin specimen.

a) The horizontal load and maximum bending moment bearing capacity of the latest repair scheme, namely specimen Rep-3, exhibits an increase of almost 100% when compared with the corresponding bearing capacity of the virgin specimen. **b)** When this comparison is made between the latest repair scheme Rep-3 and repair scheme Rep-2 the increase is of the order of 25%. Moreover, the new anchoring scheme does not cause an abrupt fracture of the CFRP at the anchoring device. This is reflected in figures 17a and 17b by the fact that the obtained response of specimen Rep-3 extends to relatively large displacement and rotation values. **c)** A reduction in the initial stiffness appears to be present in specimen Rep-3 when its obtained cyclic response in terms of the envelope curve of figures 17a,b is compared to the corresponding curves of specimen Rep-2 and the virgin specimen. This must be attributed to the fact that most parts of specimen Rep-3 have been subjected to three full loading sequences except the new parts of the CFRP. **d)** Rep-1 corresponds to the least effective repair scheme due to the detaching of the CFRP layers.

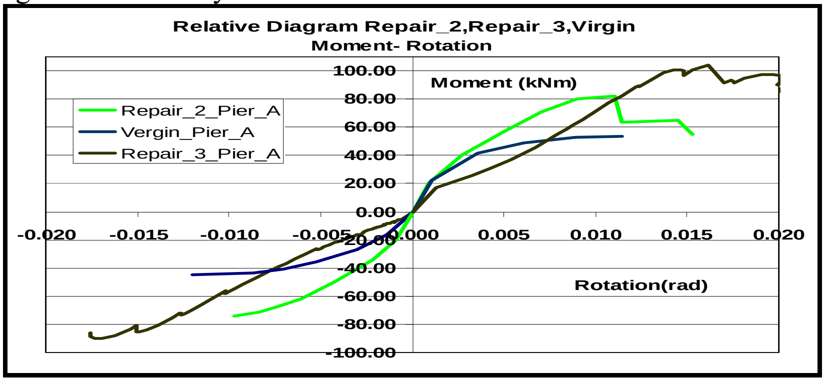


Figure 17b. Flexural response of repaired Rep-3, Rep-2 and virgin specimens.

7. CONCLUSIONS

- The upgrading of the flexural behavior of vertical R/C structural elements was investigated utilizing the possibility of attaching longitudinal CFRP layers that can be stretched developing tensile forces externally at the opposite sides of these elements. Critical aspects for their satisfactory performance are the bonding of the CFRP layers as well as the effective transfer of the tensile forces to the foundation block.
- The bonding of the CFRP layers at the sides can be improved by bolting schemes that in this way increase the cooperation between the CFRP layers and the concrete part.
- The transfer of the tensile forces that develop at the CFRP layers to the foundation is a difficult technical problem. Two schemes were tried. The 2nd scheme is more practical and was successful in mobilizing sufficiently the available capacity of the applied CFRP layers in such a way that it resulted in approximately 100% increase in the flexural capacity when compared to the initial flexural capacity of the virgin specimen before the application of the CFRP layers.
- The applicability of such an anchoring system must be validated in a more general way before final practical conclusions can be reached.
- Such an upgrading of the flexural capacity may lead to the appearance of the shear mode of failure. However, the shear capacity can be increased with relative ease by closed CFRP hoops.

ACKNOWLEDGEMENTS

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