Proceedings of the 8th U.S. National Conference on Earthquake Engineering
April 18-22, 2006, San Francisco, California, USA
Paper No. 1965

RETROFITTING R/C BRIDGE PIER TYPE CROSS-SECTIONS WITH PARTIAL CONFINEMENT EMPLOYING CARBON FIBER REINFORCING PLASTICS

G. C. Manos[1] and V. Kourtides[2]

ABSTRACT

Results and conclusions are presented from an experimental investigation with identical column-specimens, constructed with prototype materials having a height of 1600mm and a cross section 300mm by 200mm. They represent models of a part of a bridge-pier near its base, with or without partial confinement of Carbon Fiber Reinforcing Plastic (CFRP) layers. They were subjected to compressive loads as this type of stress field is expected to develop at the base of such vertical members under combined vertical loads and seismic actions, where undesired compression failure may develop. The retrofitting of this type of reinforced concrete cross sections, with h/b ratio larger than 1.5, is aimed at prohibiting, up to a point, such compression failure. This type of partial confinement may also be applied to retrofitting similar vertical structural members with non-accessible sides. With the successful application of this partial confinement, an increase of almost 50% was observed in this compression capacity of the test specimens. Moreover, the deformability of these specimens was substantially increased, demonstrating the effectiveness of this type of partial confinement. It was also demonstrated from the experimental sequence that critical factors for this effectiveness were the type of anchorage of the CFRP partial confinement and the number of CFRP layers.

1. Introduction

The upgrading of reinforced concrete (R/C) cross-sections, with one side rather longer than the other (h/b > 1.5), by partial application of CFRP (Carbon Fibre Reinforcing Plastic) confinement is investigated here (Figure 1). This partial application of CFRP confinement is aimed at the retrofitting of bridge-pier type R/C cross-sections in order to prohibit, up to a point, the development of premature compressive failure at the base of the pier due to combined compression and flexure from seismic loads (Figure 2.). The performance of such structural elements was studied extensively in the past (Pinto 1996). This type of partial confinement may also be applied to upgrading vertical structural members with non-accessible sides. Design guidelines for rectangular FRP jackets applied on rectangular columns have been proposed with the limitation that the cross-sections have aspect ratio h/b < 1.5 (Tsonis 2004). For higher aspect ratios it is recommended to design a circular or oval jacket. However, it is expected that for

[1]Professor, Dept. of Civil Engineering, Aristotle University of Thessaloniki, GREECE, 54006.
[2]Research Assistant, Dept. of Civil Engineering, Aristotle University of Thessaloniki, GREECE, 54006.

rectangular cross sections with aspect ratios larger than 1.5 the radius of a circular or rectangular jacket will be too large and will result in ineffectual confinement and will prove costly and impractical. For this reason it is desirable to investigate alternative schemes for increasing the confinement of rectangular cross-sections with relatively large aspect ratio without resorting to complete circular or oval jackets. Such a scheme is studied here using CFRP layers that do not extend all around the cross-section (Fig. 1 "*partial confinement*").

To compensate for the fact that the CFRP layers do not enclose the cross-section entirely, anchorage of these layers must be provided, as shown schematically in Figure 1. To this end, a laboratory investigation was carried out to study the effectiveness of such partial confinement together with alternative anchorage schemes. As will be explained, this effectiveness was tested by subjecting the specimens only to compressive loads. Despite this limitation, as will be demonstrated from the results of this investigation, the most significant aspects of the critical factors for this "*partial confinement*" scheme were brought to light.



Figure 1. R/C cross-sections with one side longer than the other (h/b>1.5) and CFRP partial confinement.

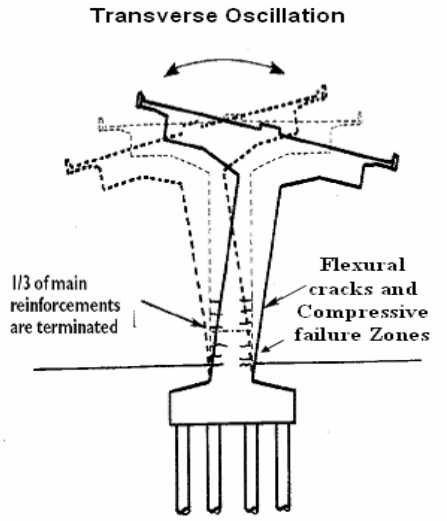


Figure 2: Bridge pier failure mode

2. The formation of the test specimens.

The initial cross-section, which formed the basis of the tested specimens, is depicted in figures 3a and 3b with an aspect ratio h/b equal to 2.5. This is a rectangular cross section of a bridge pier model structure, which was tested at the Volvi-Greece European Test Site in the framework of the European project Euro-Risk (Manos et.al. 2004). This cross section was intentionally designed to develop flexural mode of failure at the base of the pier; moreover, it was desirable to find ways to retrofit such specimens by prohibiting premature compression failure at the base by means of partial CFRP confinement. The effectiveness of the partial CFRP confinement is studied by subjecting the tested specimens only to pure compressive loads. This type of stress field is expected to develop in the base of such vertical members under combined vertical loads and seismic actions, where undesired compression failure may develop. In order to limit the maximum level of compressive loads required to bring to failure such a cross-section with the loading arrangements available, the tested specimens had a cross section (figure 4) of 200mm (7.87inches) by 300mm (11.81inches) (instead of 200mm by 500mm of the initial cross-section, figure 3a). Moreover, in order for the tested specimens to form compression failure at the same part of the cross-section where such failure would develop at the base of the initial bridge pier model, one part of the tested cross-section was left identical to the initial cross-section (the one that is marked in figure 4 as weak) whereas the remaining part was strengthened both with longitudinal and in particular, with transverse reinforcement (the one marked in fig. 4 as strong).

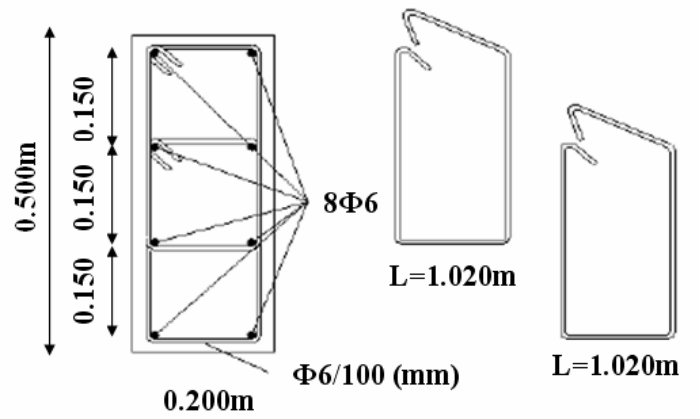


Figure 3a. Initial cross-section with h/b ratio = 2.5

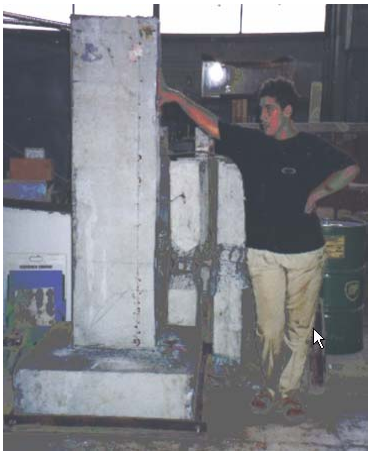


Figure 3b. Bridge pier model specimen tested at the laboratory

In this way, with the compression capacity of the weak part being smaller than that of the strong part, the compression failure was expected to develop at the weak part. This proved to be correct during the experiments, as will be shown in the following sections. The CFRP partial confinement was applied at the weak part, as is shown at the right hand side of figure 4. Then, by studying the resulting bearing capacity and mode of failure under compression of the tested specimens (with or without partial confinement) the effectiveness of such a repair could be demonstrated and classified as listed in Table 1.

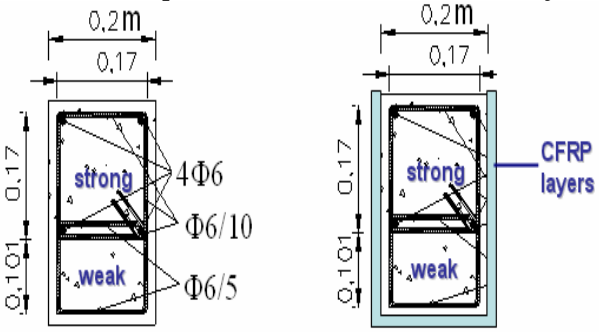


Figure 4. Test specimens without and with partial CFRP confinement.

Table 1. Characterization of the effectiveness of the partial confinement

Grade	Compression failure mode	Increase in the compressive capacity (compared to the unconfined specimens)	Effectiveness of the partial confinement
1	Of the weak part as without the partial confinement	Small increase	**low**
2	Of the weak part as without the partial confinement	Considerable increase	**Considerable**
3	Of both the weak part and the strong parts	Substantial increase	**Very effective**

3. Construction of the test specimens.

Ten identical specimens were constructed and eight of them were used in the current experimental sequence (see Table 2). All specimens were reinforced in the same way and were

cast at the same time with the same mixture aiming for similar plain concrete strength values. The reinforcing details are depicted in figure 5. As can be seen, the total height of the specimens was 1600mm (5feet 6.33inches). They had a mid-part height of 580mm (1 foot and 10.83 inches) that was left to develop the compression failure (figure 5 part denoted as CROSS SECTION A). The cross section of this mid-part was the one shown in figure 4, including the two distinct parts (the weak and the strong). The two edges of the specimens, with a height of 510mm (1 foot and 8.08 inches) each, were confined during the experiment with strong steel brackets covering these parts from all sides thus prohibiting any compressive failure developing at those two edges (see figure 6).

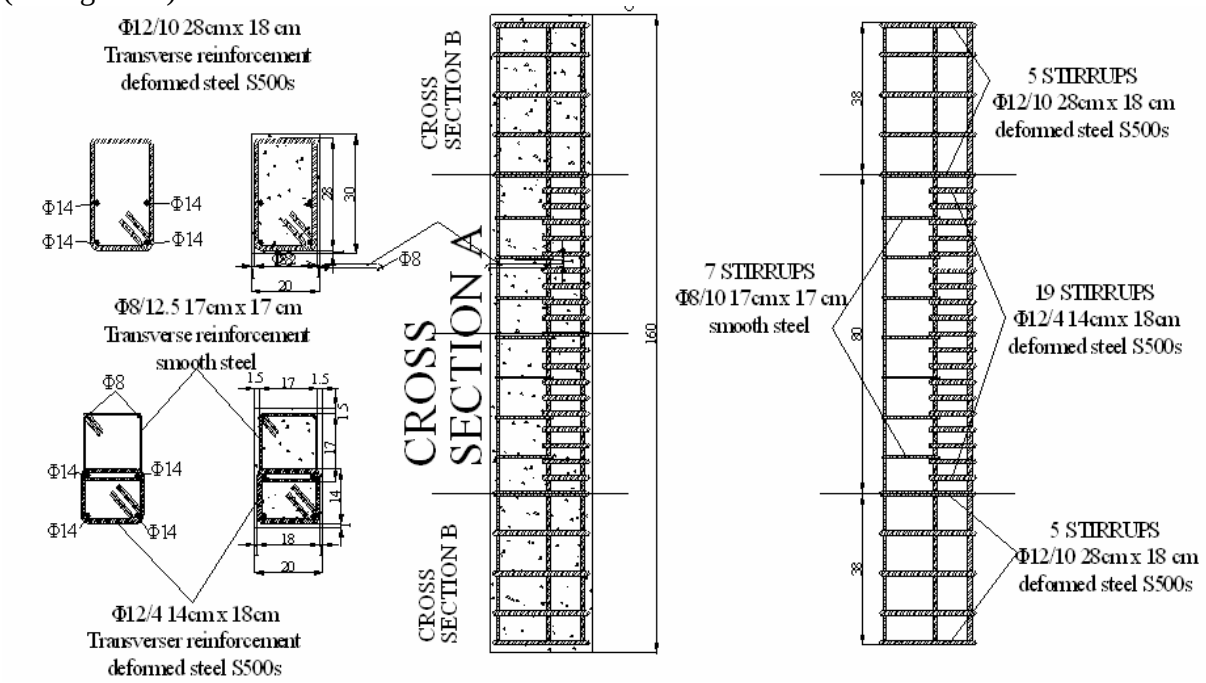


Figure 5. Reinforcement details common to all specimens.

The partial CFRP confinement was attached only on the three sides of these specimens covering the weak part and leaving the fourth side (of the strong part) free without any CFRP layers (figure 4). There were 8 virgin specimens, namely 1, 1a, 3. 3a, 4, 4a, 5, and 5a (Table 2). These specimens were tested in their virgin state in which some of them were without partial CFRP confinement whereas the rest had the partial CFRP confinement applied to them from the beginning. The second column of table 2 indicates the partial confinement condition of the virgin specimens. The testing sequence of these virgin specimens is signified as Test 1. Most of these specimens were repaired after they had reached their limit state during their previous test. In all the repaired specimens the CFRP partial confinement was applied. This sequential test sequence of the repaired specimens is signified as Test 2 (for the 1st repair), Test 3 (for the 2nd repair) etc. (see column 3 of Table 2). In the same column the number of CFRP layers used in the partial confinement for the repaired specimens is also indicated. The total number of specimens, virgin and repaired, was seventeen. In Table 2 the unconfined concrete compressive stress is also listed, found from cylinder with diameter 150mm (5.91inhes) and 300mm (11.81inches) height; these cylinders were obtained during the casting of each virgin specimen. The anchorage of the CFRP layers was applied along the two long sides, which were common to both the weak and the

strong parts. The main load that was applied was axial compression, although in limited specimens the axial compression was combined with bending, which is not reported here. From the observed behavior, the effectiveness of the applied partial confinement could be deduced. As shown in Table 1, this judgment was based on the level of the bearing capacity combined with the type of compression failure that was formed (at the weak or strong part). Moreover, the observed behavior of the various parts of the test specimens, such as the CFRP layers and their anchorage, helped to identify the factors that bear an adverse or beneficial influence on these aspects of the behavior.

Table 2: Description of test specimen with their corresponding concrete strength

Virgin Specimens	CFRP Confine-ment	Repaired Specimens	Plain Concrete Strength (Mpa)*
Specimen 1 Test 1	No	Test 2 3+(2) CFRP	28.0
Specimen 1a Test 1	3 CFRP layers	Test 2 3 GFRP	25.8
Specimen 3 Test 1	No	Test 2 3+(2) CFRP	27.6
Specimen 3a Test 1	5 CFRP layers	Test 2 5 CFRP	27.6
Specimen 4 Test 1	5 CFRP layers		27.7
Specimen 4a Test 1	5 CFRP layers		27.7
Specimen 5 Test 1	5+(2) CFRP layers	Test 2, 5+2 CFRP Test 3, 5+2 CFRP Test 4 7 CFRP	27.6
Specimen 5a Test 1	No	Test 2, 7 CFRP Test 3 7+4 CFRP	25.8



Figure 5. Specimen with confining steel brackets at the edges and partial CFRP confinement at the mid-part

* 1Mpa = 0.145ksi, 1ksi=6.895Mpa

4. Critical parameters and their variation

The following parameters were critical, as seen from the results contained in Table 3.

1st. The type of anchorage of the CFRP layers , *2nd. The number of the CFRP layers.*

The second parameter becomes critical only if the first parameter performs satisfactorily. A large number of specimens (1 , 1a, 3, 3a, 4 and 4a) exhibited failure of the anchorage of the partial confinement thus limiting the effectiveness of the partial confinement to low levels. Consequently, the increase in the compressive bearing capacity in this case was relatively modest. The compressive load was monitored by continuous sampling throughout the test. The "*Average Stress at failure***"** listed in table 3 is found by dividing the compressive load by the gross cross-sectional area of each specimen. Listed in Table 3 are certain particulars of the anchorage of the CFRP layers. Anchors-1 signifies bolts of 7mm (0.275inches) diameter and 60mm (2.36inches) length that are not penetrating the cross-section in its whole width, whereas Anchors-2 signifies bolts of 10mm (0.394inches) diameter that penetrate the whole section (220mm length).

Table 3: Summary of test results together with the basic specimen characteristics

Specimen No	Virgin	Repaired	Number of CFRP layers	Anchors-1	Anchors-2 + washers	Average Stress at failure (Mpa)	Failure Mode
1 Test 1	Yes	No	No	No	No	41.12 (146.9%)*	Weak part
1 Test 2	No	Yes/ EMACO	3 (+2)	Yes	yes	41.69 (148.9%)	Bolts
1a Test 1	Yes	No	3	Yes		45.78 (177.4%)	Pull out Anchors-1
3 Test 1	Yes	No	No	No		40.79 (147.7%)	Weak part
3 Test 2	No	Yes	3 (+2)	Yes	Yes	45.78 (165.9%)	anchorage
3a Test 1	Yes	No	5	Yes	Yes	47.09 (170.6%)	anchorage
3a Test 2	No	Yes/ EMACO	5	Yes	Yes	42.51 (154.0%)	anchorage
4 Test 1	Yes	No	5	No	Yes weak	46.60 (168.2%)	anchorage
4a Test 1	Yes	No	5	No	Yes weak	45.53 (164.4%)	anchorage
5 Test 1	Yes	No	5 (+2)	No	Yes strong	53.96 (195.5%)	Steel bracket
5 Test 2	Yes	-	5 (+2)	No	Yes strong	55.26 (200.2%)	Steel bracket
5 Test 3	-	Top / EMAKO	5 (+2)	No	Yes Strong	53.96 (195.5%)	CFRP mid-height
5 Test 4	No	Yes/ EMAKO	7	No	Yes Strong	58.86 (213.3)	Strong stirrups
5a Test 1 bending	Yes	No	No	No	No	40.88 (158.4%)	Weak part
5a Test 2	No	Yes	7	No	Yes Strong	57.23 (221.8%)	CFRP mid-height
5a Test 3	No	Yes	7 +4	No	Yes Strong	60.17 (233.2%)	Strong part

* As % of the corresponding plain concrete strength.

For specimens 5 and 5a, due to the improvement of the anchoring details of the partial confinement, the increase in the compressive bearing capacity of these specimens was 50% higher than the observed bearing capacity of similar specimens with no partial CFRP confinement. When the maximum compressive bearing capacity achieved with the partial confinement is compared with the corresponding plain concrete strength value, a 230% increase can be observed. Moreover, the compressive failure in this case involved both the weak and the strong part thus improving substantially the effectiveness of the partial confinement and allowing the employment of a large number of CFRP layers.

5. Instrumentation to obtain the average stress-strain behavior

Apart from monitoring the compressive load, the deformations of the mid-part were also continuously recorded throughout each experiment with displacement measurements taken at each side of the cross-section. Eight displacement sensors (two at each side) were employed to record the deformations of the mid-part. Although the deformation of this mid-part was far from uniform, as can be seen from the obtained displacement measurements of the weak and strong parts (figure 7), the average axial displacement, which was found by averaging the measured displacement values at all four sides of each specimen, is mostly used here as an indication of the deformability of each specimen. By dividing this average axial displacement by the height of the mid-part an average axial strain could also be obtained in this way. The following discussion of the observed behavior of each specimen is based on diagrams of average axial stress versus average axial strain found from the previously described averaging process. More detailed study on the obtained non-uniform deformability for each specimen will be carried out at a future stage. An additional measurement that was obtained during the experimental sequence was the axial strain that developed at the CFRP layers of the partial confinement of the mid-part. These CFRP strain measurements are an additional indication of the effectiveness of the partial confinement.

6. Discussion of the results

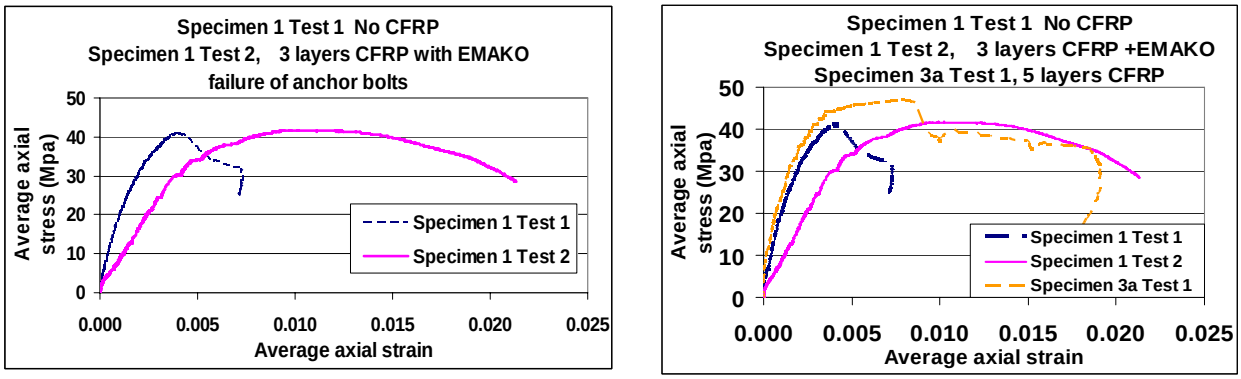


Figure 6a and b. Partial confinement of low effectiveness

6.1. Partial confinement of low effectiveness

In figures 6a and 6b the obtained behavior of specimen1 (Test 2) with 3 CFRP layers and specimen 3a (Test 1) with 5 CFRP layers is compared with specimen 1 test 1 (no partial confinement). Specimen 1 test 2 was formed from specimen 1 test 1 by repairing the failed specimen 1 test 1 with special (low shrinkage) concrete as well as with 3 layers of CFRP forming the partial confinement. This repaired specimen failed in compression with almost the same capacity as the previously-tested virgin test with no partial confinement, but with larger deformability. The effectiveness of the partial confinement is low and it is due to the failure of the anchor bolts of the applied confinement. In figure 6b the observed behavior of specimen 3a Test 1 is also included. This is a virgin specimen that had a 5-CFRP layer partial confinement. Despite the increase in the CFRP layers, the observed effectiveness of the partial confinement is low as was for specimen 1 test 2, again because of the failure of the anchor bolts.

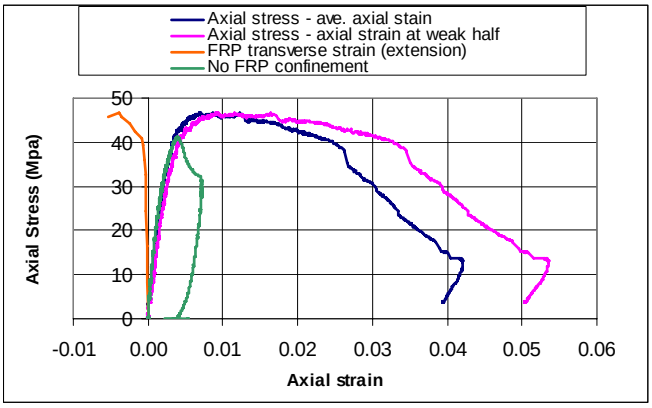


Figure 7. Spec. 4 Test 1 (5 layers CFRP) Comparison with Spec. 1 Test 1 (no confinement)

In figure 7 the observed behavior of specimen 4 test 1 is depicted. This was a virgin specimen with 5 CFRP layers partial confinement. In this case, a certain alteration was applied in the anchor bolts, by increasing their length. However, this was not sufficient to improve accordingly the effectiveness of the partial confinement, which was again linked to the failure of the anchor bolts. The failed virgin specimen without the partial confinement is shown in figure 8a whereas figure 8b depicts the failure of the anchor bolts for the "low effectiveness" partial confinement.



Figure 8a. Virgin Specimen without confinement



Figure 8b. Failure of anchor bolts Low effectiveness of partial confinement



Figure 8c. Tensile failure of CFRP Layers. Considerable effectiveness of partial confinement

6.2. Partial confinement of considerable effectiveness

In figures 9a and 9b the obtained behavior of specimen 5 (Test 3) with 5 (+2) CFRP layers is compared to specimen 1 test 1 (no partial confinement). Specimen 5 test 3 was formed by repairing a previously failed virgin specimen with special (low shrinkage) concrete as well as with 5 layers of CFRP forming the partial confinement. An additional two (+2) CFRP layers were applied at the part of the section where the anchor bolts were placed. This repaired specimen failed in compression with a modest increase (31%) in its capacity when compared with the capacity of the virgin unconfined specimen. The effectiveness of the partial confinement in this case was classified as considerable. This was due to an alteration in the anchoring of the partial confinement which proved to be relatively successful. The limit state for this specimen commenced with the tensile failure of the CFRP layers at the central zone and was accompanied, as expected, by a consequent compressive failure of the neighboring weak part of the section. This is depicted in figure 8c where the anchor bolts, which were left intact, are also shown. In figure 9b, the comparison is extended to include specimen 4 (Test 1), in which the partial confinement exhibited low effectiveness due to the failure of the anchor bolts (section 6.1).

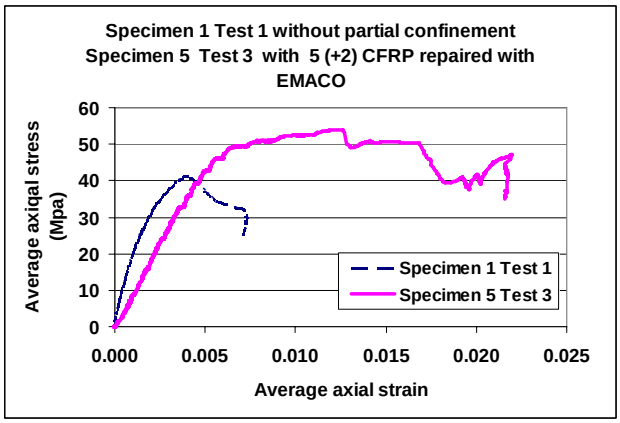


Figure 9a.

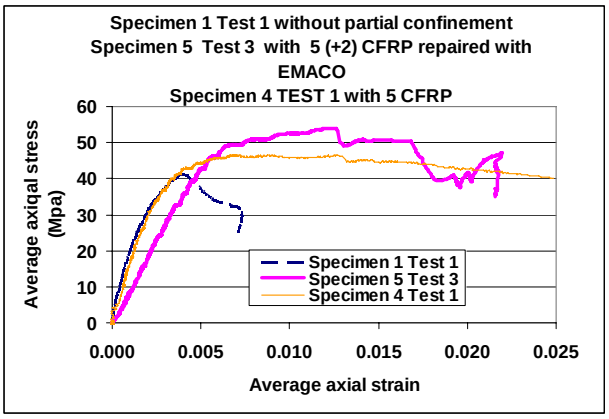


Figure 9b

6.3. Very effective partial confinement.

In figure 10a, the behavior of specimens 5 (Test 4) and 5a (Test 2) is compared with the behavior of specimens 1 test 1 (with no partial confinement) and 5 (Test 3) discussed in section 2. Specimens 5 (Test 4) and 5a (Test 2) were formed by repairing previously failed specimens with partial confinement of 7 layers of CFRP. Moreover, all the anchoring of their partial confinement was made with bolts going through the whole width of the strong part of the repaired section (see Table 3 and figure 4).

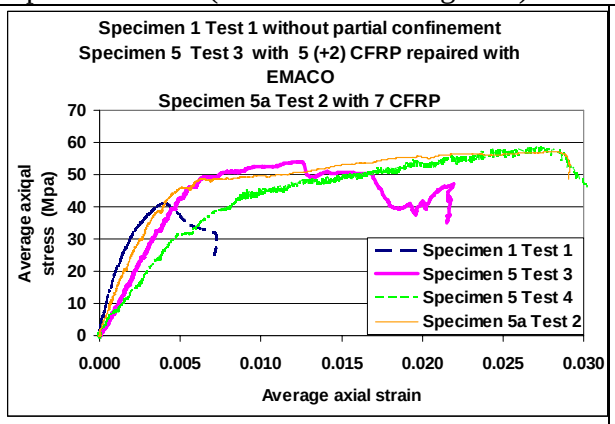


Figure 10a

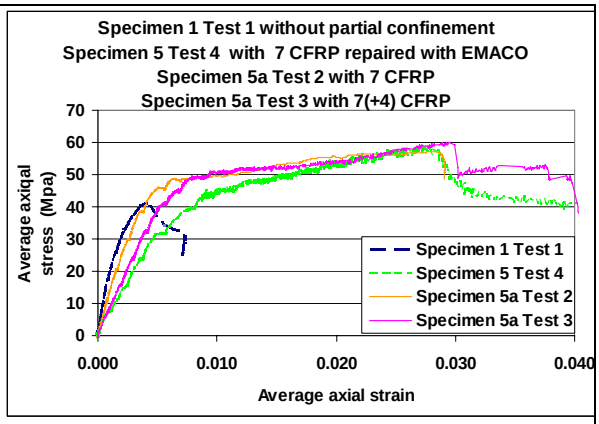


Figure 10b

As can be seen in figure 10a, a substantial increase (40%), in the bearing capacity as well as in the deformability, resulted from the described partial confinement for these two specimens. Their behavior was in this way better than the behavior of specimen 4 (Test 1) which was classified before as one of considerable effectiveness of the partial confinement (section 6.2). Based in this increased capacity and deformability of specimens 5 (Test 4) and 5a (Test 2) they were classified as specimens with very effective partial confinement. The limit state of specimen 5 (Test 4) was accompanied with the failure of the stirrups of the strong part whereas the limit state of specimen 5a (Test 2) was accompanied with the tensile failure of the CFRP layers at the central zone. In figure 10b the observed behavior of specimen 5a (Test 3) is compared with that of specimens 5 (Test 4) and 5a (Test 2) previously discussed.



Figure 11a.

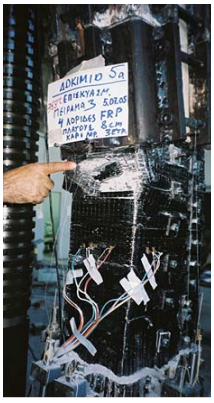


Figure 11b

Specimen 5a Test 3 had a partial confinement formed by 7 layers of CFRP. Moreover, the area sustaining the anchor bolts was strengthened by additional four (+4) layers of CFRP. Apart from the anchor bolts going through the whole width of the strong part of its section, the stirrups of this strong part were also strengthened (figure 11a). This time the increase in the bearing capacity was 46%; the increase in the deformability was also quite substantial. Thus, the behavior of this specimen is also one with very effective partial confinement. The observed limit state was accompanied with the compressive failure of the CFRP layers at the mid-part near the steel brackets (figure 11b).

Conclusions

1. The undesired compression failure expected to develop in the base of vertical members with reinforced concrete cross sections having h/b ratio larger than 1.5 under combined vertical loads and seismic actions is studied through specially formed specimens subjected to uniform compression. The retrofitting of such specimens with partial CFRP confinement is aimed at prohibiting, up to point, such compression failure. This type of partial confinement may also be applied to upgrading vertical structural members with non-accessible sides.

2. From the results of the experimental investigation with identical specimens, with or without this type of partial CFRP confinement, the successful application of such partial confinement was demonstrated. An increase of almost 50% was observed in the compression bearing capacity of some of the tested specimens. Moreover, the deformability of these specimens was substantially increased, demonstrating the effectiveness of this type of partial confinement.

3. It was found from the experimental sequence that critical factors for this increase were the type of anchorage of the CFRP partial confinement and the number of CFRP layers. Successful anchoring of the CFRP layers allowed this partial confinement to become effective and to permit the use of a larger number of CFRP layers. In the present study alternative anchoring schemes were tried with limitations imposed by the geometry of the model cross-section. Similar limitations imposed by the geometry and the reinforcement of the cross-section will also dictate the design of such an anchoring scheme for a prototype cross-section. Further investigation on the performance of such prototype anchoring arrangements may be necessary.

Acknowledgements

This work was partially supported by the European Union in the framework of the project Euro-Risk EVG1-CT-2001-00040.

References

Manos, G.A., et.al (2004) “Dynamic and Earthquake Response of Model Structures at the Volvi – Greece European Test Site”, *Proceedings of the 13th World Conference of Earthquake Engineering*, Vancouver, B.C., Canada, August 1-6, 2004. Paper No. 787.

Pinto A. V., editor 1996. Pseudodynamic and Shaking Table Tests on R.C. Bridges. *ECOEST PREC*8* Report No. 8, November 1996.

Tsonis, G (2004) “Seismic Assessment and Retrofit of Existing Reinforced Concrete Bridges”, Ph.D. Thesis, Politecnico di Milano.