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Different application methods on CFRP- and GFRP- confined concrete: experimental results

Marina L. Moretti[1], and Eftichios Arvanitopoulos[2]

[1] National Technical University of Athens, Athens, Greece
[2] University of Thessaly, Volos, Greece

ABSTRACT: Jacketing of columns using fiber reinforced polymers (FRP) is a method often used for strengthening reinforced concrete columns in substandard buildings. In this paper the experimental results of ten (10) plain concrete cylinders of 152-mm diameter and 305-mm height, with unconfined compressive strength of 18 MPa, wrapped with carbon FRP (CFRP) and glass FRP (GFRP) jackets are presented. Different application methods of the FRP are examined in relation to the effectiveness of the FRP. More specifically, two brushes of different hardness, a soft and a hard brush, are used to apply both CFRP and GFRP jackets. Moreover, dry and wet lay-up methods, as well as two different types of CFRP are tested. Results are discussed in terms of confined strength and strain measurements along the jacket perimeter.

1 INTRODUCTION

A systematic experimental study has been performed in order to investigate a number of parameters that may affect the confinement provided by FRP jackets (Arvanitopoulos, 2014). In this paper only a part of this investigation is presented consisting of 10 (ten) plain concrete cylinders with compressive strength 18 MPa and a single layer of FRP with overlap length equal to 100 mm. The main criterion for choosing the specific specimens was to discuss whether different methods of FRP application may influence the activation of the FRP jacket. The test results included study the effect of using a hard or soft roller at the application of one layer of carbon FRP (CFRP) and glass FRP (GFRP) by testing two identical specimens in each case for the dry lay-up method. For the same CFRP material one cylinder with wet lay-up method was tested, and also a cylinder with one layer of a more dense CFRP jacket.

2 EXPERIMENTAL PROGRAM

2.1 Test specimens and materials

2.1.1 Materials

All specimens were cast simultaneously from a single ready-mix concrete batch with 28-days cylinder compressive strength around 18 MPa. The cylinders were removed from the molds two or three days after casting, and they were cured for 28 days in laboratory conditions.

Although in the majority of published experimental studies the wet lay-up technique is used, in this experimental program dry lay-up was generally applied in the FRP jackets. Only in one cylinder wet lay-up was used for comparison purposes. The reason for this choice is that while dry lay-up is very often used in retrofitting RC columns of buildings in Greece very few test results are available in the literature with dry lay-up application (Rousakis and Tepfers, 2004). The properties of the unidirectional FRP sheets and epoxy resin used for the jackets (manufacturer's data) are provided in Table 1.

In dry application, both for substrate primer and for impregnating / laminating resin Sikadur®-330 was used (a two-part, thixotropic epoxy based impregnating resin). In wet application, for substrate primer resin Sikadur®-330 was applied while Sikadur®-300 was used for impregnating the fabric. All specimens were left to cure at least 7 days after the application of the FRP before testing according to the manufacturers' recommendations.

Table 1. Fiber Reinforced Polymer (FRP) characteristics for Carbon FRP (CFRP) and Glass FRP (GFRP)

Dry lay-up				
FRP characteristics	Areal weight (g/m^2)	Thickness (mm-per ply)	Tensile modulus (N/mm^2)	Rupture strain ε_{fu} (%)
CFRP (SikaWrap®-230 C)	235	0.129	230000	1.70
CFRP (SikaWrap®-300 C)	309	0.171	242000	1.43
GFRP (SikaWrap®-430 G)	445	0.172	76000	2.80
Resin Sikadur®-330			4500	0.90
Wet lay-up (specimen WC1)				
FRP characteristics	Areal weight (g/m^2)	Thickness (mm-per ply)	Tensile modulus (N/mm^2)	Rupture strain ε_{fu} (%)
CFRP (SikaWrap®-230 C)	235	0.129	230000	1.70
Resin Sikadur® -300			3000	1.50
Resin Sikadur® -330			4500	0.90

2.1.2 Properties of test specimens

The specimens presented in this paper consist of 10 plain concrete cylinders 152 mm in diameter and 305 mm in height subjected to axial compression. The cylinders were jacketed with a single layer of FRP by manual lay-up with all fibers oriented in the hoop direction, perpendicular to the axis of the cylinders. Dry lay-up was used to apply the FRP jacket, with the exception of one specimen with CFRP of 235 g/m^2 in which wet lay-up was applied, designated as specimen WC1. One type of GFRP and two types of CFRP fabrics were tested (see Table 1).

The effect of using a hard (H) or a soft (S) roller to apply the FRP fabric on the specimens was investigated for jackets GFRP 445g/m^2 and CFRP 235g/m^2 (indicated by H or S in the third constituent of the specimens' name). Two identical cylinders were prepared and tested in each case (1, 2 in the last character of the specimens' name) resulting in total in 8 specimens. Another type of CFRP fabric of 309g/m^2, in specimen C1(300g) with dry lay-up was also tested. All specimens had the same overlap length equal to 100 mm.

In the specimens' name the first letter corresponds to the type of fabric (C for carbon, G for glass), and is followed by number 1 in all cases to indicate that one layer of FRP was used. The third letter, S or H, indicates the use of a soft or hard roller for the FRP application, respectively. An example is given: Specimen G1S2 indicates that the jacket was Glass FRP (G), one layer of FRP (1), applied with a soft roller (S), and that it this is the second (2) of the two identical specimens tested.

2.1.3 Specimens preparation

The ends of the concrete cylinders were capped with high-strength sulfur prior to the FRP-application, leveled and checked with a suitable straight edge so that they are parallel. In all specimens priming coat was applied through a soft roller, while the application of the FRP fabric was performed either by a soft or a hard roller, as described in the section of the specimens' properties.

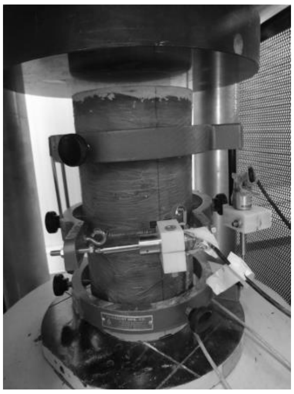
2.1.4 Instrumentation and testing

Axial and lateral deformations of the specimens were measured through linear displacement variable transducers (LVDTs), which were placed on a pertinent Humboldt compressometer mounted in the middle portion of the cylinder, as shown in Figure 1a. The hoop strains were measured by unidirectional strain gages 20 mm in length that were bonded to the FRP along the perimeter at mid-height of the specimen. One strain gage was placed on the axis of the overlap length (SG 1, Figure 1b), another at 180^o in the anti-diametrical position (SG 3), and in some specimens also strain gages at 15 mm from the start (SG 4) and the end edge (SG2) of the overlap length of the FRP fabric.

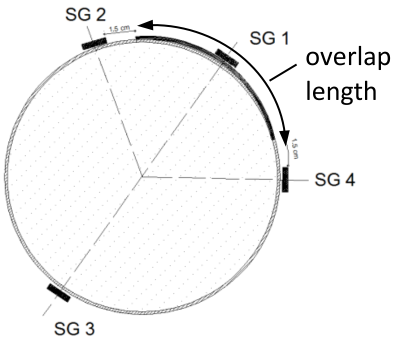
2.2 Test results

2.2.1 General observations

The failure pattern does not seem to be influenced by the way the FRP was applied as it may be seen in Figures 2 and 3.



(a) Steel frame with LVDTs at middle part measuring axial and lateral deformation



(b) Strain gages
SG4=start-, SG2=end-of overlap length

Figure 1. Instrumentations

G1S1 G1S2 G1H1 G1H2

Figure 2. Failure patterns of GFRP specimens.

C1S2 C1H2 C1(300g) WC1

Figure 3. Failure patterns of CFRP specimens.

Table 2 provides the peak axial compressive strength, f_{cc}, and the corresponding axial and lateral strain, ε_{cu} and $\varepsilon_{lateral}$, respectively (from LVDTs), as well as the FRP maximum lateral strain, $\varepsilon_{f,max}$, and lateral strain at the axis of the overlap length, $\varepsilon_{f,overlap}$, from SGs at mid-height (Figure 1b).

Table 2. Test results at maximum compressive strength.

Specimen	f_{cc} (MPa)	ε_{cu} $(\times 10^{-3})$	$\varepsilon_{lateral}$ $(\times 10^{-3})$	$\varepsilon_{f,max}$ $(\times 10^{-3})$	$\varepsilon_{f,overlap}$ $(\times 10^{-3})$	$\varepsilon_{f,overlap}/\varepsilon_{f,max}$	$\varepsilon_{f,max}/\varepsilon_{fu}$
C1S1	34.8	-24.6	19.7	15.2	7.8	0.51	0.89
C1S2	39.7	-20.2	18.3	15.2	9.9	0.65	0.89
C1H1	36.4	-23.1	17.1	14.4	8.3	0.58	0.85
C1H2	37.4	-18.9	16.3	12.9	7.4	0.57	0.76
C1(300g)	39.7	-13.2	15.8	11.4	5.9	0.52	0.80
WC1	39.6	-17.7	15.5	13.4	7.9	0.59	0.79
G1S1	26.4	-11.4	16.4	16.2	8.6	0.53	0.58
G1S2	27.5	-10.3	16.7	14.3	8.8	0.62	0.51
G1H1	25.8	-12.3	13.4	13.2	8.9	0.67	0.47
G1H2	26.9	-13.0	18.4	14.4	8.1	0.56	0.51

The peak confined concrete strength, f_{cc}, and axial strain, ε_{cu}, are higher for CFRP than for GFRP specimens in general because of the higher confining capacity of CFRP material.
Comparing the axial strength, f_{cc}, of the 6 CFRP cylinders it is observed that specimens C1S2, WC1 and C1(300g) have 10% higher strength than the average strength of the other three specimens. It is noted that specimens C1S1, C1S2, C1H1 and C1H2 were tested on the same day (i.e. 36 days after casting). Specimens WC1 and C1(300g) were tested 84 days and 96 days, respectively, after casting, which explains the increased value of f_{cc}, for these two specimens. The increased strength of C1S2 has to be attributed to other parameters and, as it seems, may not be considered as representative of the behavior of the above group of four specimens. In Figure 4 are depicted the axial stress-lateral strain curves for the four types of CFRP-jacketed cylinders, and also for an unconfined plain concrete cylinder. The lateral strain values are the strains measured from the lateral LVDT (Figure 1a) at mid-height of the column, which is in general higher than the respective lateral strains measured from the strain gages mounted on the FRP (see also section 2.2.3).

Furthermore, it is interesting to observe that specimens WC1 and C1(300g) have identical compressive concrete strength $f_{cc} \cong 39.6$ MPa and lateral strain measured by the LVDT $\varepsilon_{lateral}$=15.7% but different maximum FRP lateral strains at failure, $\varepsilon_{f,max}$ = 13.4% and 11.4%, respectively. The different value of $\varepsilon_{f,max}$ is attributed to the relatively higher thickness t_f = 0.171 mm of CFRR 309g compared to t_f = 0.129 mm for CFRR 235g used in specimen WC1, while the tensile modulus of elasticity is practically the same for the two carbon fabrics. It is recalled that different application methods were used for these two specimens, which, apparently did not result in any significant difference in the behavior of the two cylinders.

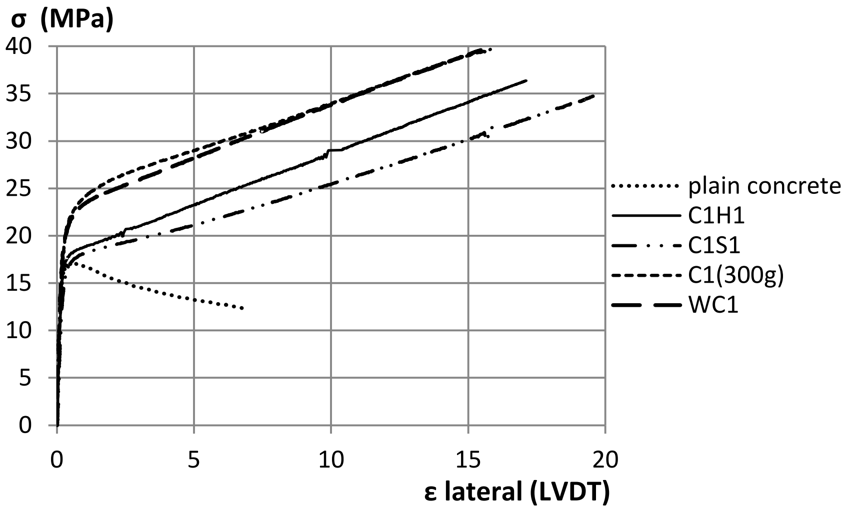


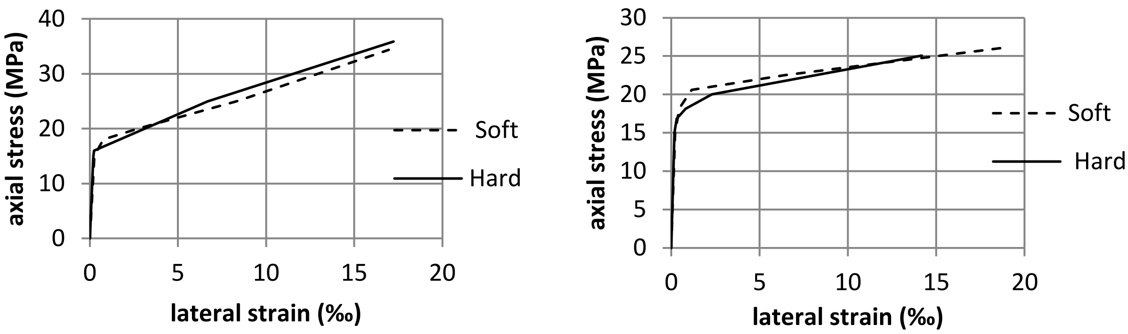
Figure 4. Comparison of axial stress - lateral strain for all types of CFRP specimens.

2.2.2 Influence of roller type on CFRP and GFRP specimens

The use of different type of roller, soft (S) or hard (H) does not seem to affect the confined concrete strength, f_{cc}. In general the maximum lateral strains of the FRP, $\varepsilon_{f,max}$, tend to be slightly higher, in average, for the specimens in which the FRP was applied with a soft roller, for both CFRP and GFRP specimens (Table 2). Regarding the ultimate axial strain, ε_{cu}, the same tendency is valid for CFRP specimens, while for GFRP cylinders the opposite is observed.

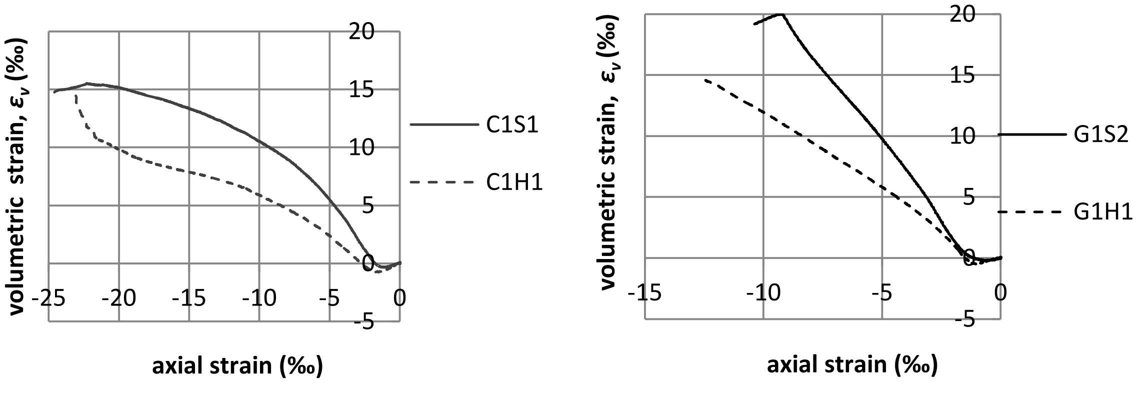
In Figure 5 the average axial stress-lateral strain curves (average over the two identical specimens, H and S in each case) are depicted for both type of fabrics. Lateral strains are from LVDT measurements. It is observed that in order to achieve the same value of axial stress higher lateral strain is required in case of S specimens, both for CFRP and GFRP.

In Figure 6 the relationship between the volumetric strain, ε_v, and the axial strain is depicted, for CFRP and GFRP specimens with different types of roller (S and H). Volumetric strain, ε_v, is defined as the trace of the strain sensor (Pantazopoulou et al. 1995), which in case of cylinders may be calculated as: $\varepsilon_v = \varepsilon_{axial} + 2\varepsilon_{lateral}$. For the same value of axial strain, the volumetric strain is lower for H specimens compared to S specimens. This observation, combined with the axial stress-lateral strain behavior (Figure 5), implies that application of the FRP through a hard roller leads to faster activation of the FRP, at lower lateral strains.



(a) CFRP soft / hard (b) GFRP soft / hard

Figure 5. Average curves for axial stress-lateral strain for CFRP specimens for soft and hard roller. Failure patterns of CFRP specimens.



(a) CFRP soft / hard (b) GFRP soft / hard

Figure 6. Volumetric strain against axial strain for CFRP and GFRP jacketed cylinders.

2.2.3 Distribution of hoop FRP strains at mid-height

Figures 7 and 8 present the strain gage (SG) measurements of the FRP hoop strains at mid-height of specimens C1(300g) and WC1, respectively, for different levels of axial strain, ε_c, as a percentage of the maximum axial strain, ε_{cu}, at peak load of each specimen (Table 2). For both specimens, the lowest lateral strain was measured by SG1 at the axis of the overlap length, as expected. At failure load the maximum lateral strain was measured by SG3 in both specimens. Similar FRP strain values are measured by SG4 and SG2 near the start and the end of the overlap length for specimen WC1. It is noted that other researchers have indicated that at the tips of the overlap length stress concentrations are bound to occur which may lead to local FRP rupture (Smith at al. 2010, Chen et al. 2010).

The ratio of the FRP hoop strains in the axis of the overlap length, $\varepsilon_{f,overlap}$, to the respective maximum strains measured at peak load (outside the overlap length), $\varepsilon_{f,max}$, ranges from 0.50 to 0.70 for all specimens (Table 2).

Moreover, the ratio of $\varepsilon_{f,max}$ to the rupture strain of the FRP, ε_{fu}, provided by the manufacturer (Table 1) for the specimens reported is in average 0.51 for GFRP and 0.83 for CFRP 235gr, and seems to be independent of the type of roller used, while ratio $\varepsilon_{f,max}/\varepsilon_{fu}$ for CFRP 309gr is 0.80 (only one specimen). This ratio is an indicator of the FRP efficiency.

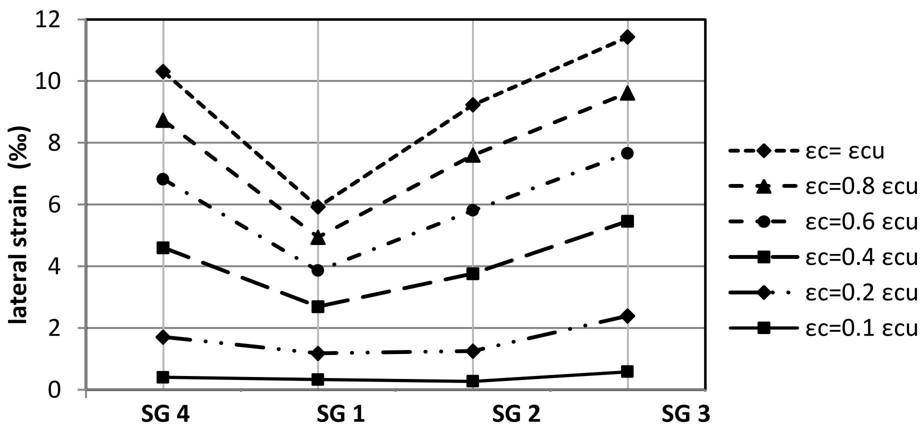


Figure 7. Strain distributions of FRP hoop strains at mid-height of specimen C1(300g) at different ratios of axial strain, ε_c, as a percentage of maximum axial strain at peak load, ε_{cu}.

3 CONCLUSIONS

Based on the results of the admittedly non-exhaustive experimental study presented in this paper, the following conclusions may be drawn.

1. The use of a soft instead of a hard roller for the application of FRP jacket does not seem to alter the axial concrete confined strength. However, in case of a soft roller more lateral deformation is needed so as to achieve the same level of confinement, both for CFRP and

for GFRP, which is probably attributed to better adherence of the FRP to the concrete when a hard roller is used.

2. The ratio of FRP hoop strains measured in the overlap region to the maximum strain measured outside the overlap region is in the range of 0.50 to 0.70 for all specimens, and does not seem to depend either on the type of fabric or on the way of FRP application.
3. The average ratio of the FRP maximum hoop strain to the rupture strain provided by the manufacturer is around 0.50 for GFRP-, and 0.80 for CFRP-jacketed cylinders. This ratio seems to be independent of the method of the FRP application (type of roller, dry or wet lay-up).

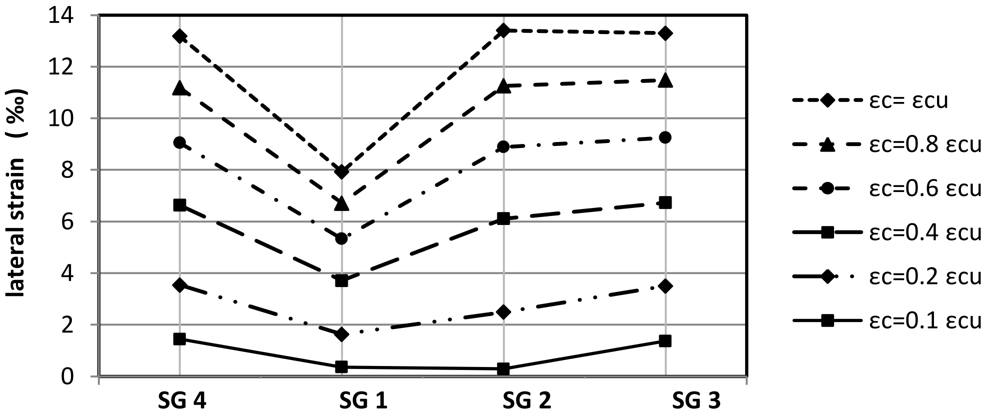


Figure 8. Strain distributions of FRP hoop strains at mid-height of specimen WC1at different levels of axial strain, ε_c, as a percentage of maximum axial strain at peak load, ε_{cu}.

4 ACKNOWLEDGMENTS

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5 REFERENCES

Arvanitopoulos, E., 2015, *Experimental study of FRP overlapping length on cylinder specimens of plain concrete*. Diploma thesis, Department of Civil Engineering, University of Thessaly (in Greek).

Chen, J.F., J. Ai, and R.H. Mills, 1995, Microstructural aspects of the mechanical response of plain concrete. *ACI Material Journal*, 92(6): 605-616.

Pantazopoulou, S.J., and T.J. Stratford, 2010, Effect of geometric discontinuities on strains in FRP-wrapped columns. *Journal of Composites for Construction*, 14(2): 136-145.

Rousakis, T., and R. Tepfers, 2004, Behavior of concrete confined by high E-modulus carbon FRP sheets, subjected to monotonic and cyclic axial compressive load. *Nordic Concrete Research,* 31: 73-82.

Smith, S.T., S.J. Kim, and H. Zhang, 2010, Behavior and effectiveness of FRP wrap in the confinement of large concrete cylinders. *Journal of Composites for Construction*, 14(5): 573-582.