ARI The Bulletin of the Istanbul Technical University VOLUME 53, NUMBER 1
Communicated by Derin Orhon

Low and Medium Strength Concrete Members Confined by Fiber Reinforced Polymer Jackets

Alper İlki, Nahit Kumbasar, and Volkan Koç
Department of Civil Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey
(Received 24 April 2003)

The objective of this study is to evaluate the effects of unconfined concrete compressive strength and the thickness of the external jacket on the stress-strain behavior of fiber reinforced polymer (FRP) jacketed concrete specimens, particularly on the strength, ductility and energy dissipation characteristics. In this experimental study, totally 16 concrete cylinder specimens are tested under axial compression. The unconfined concrete compressive strength for 8 specimens is around 30 MPa, while the remaining 8 specimens have the concrete compressive strength around 6 MPa. In each set, two unconfined specimens are tested without any strengthening, and other specimens are tested after they are externally confined by 1, 3 and 5 plies of FRP jackets in sets of two. Test results indicate a significant enhancement in compressive strength, ductility and energy dissipation for the externally confined specimens for both low and medium strength concrete, with a more pronounced effect on low strength concrete. Consequently, the investigated strengthening technique may be more preferable when dealing with structural members that have the problems of low compressive strength and ductility.

Keywords: Carbon, fiber, ductility, strength, concrete, confinement.

1. Introduction

Various researchers carried out experimental and analytical studies on the behavior of concrete jacketed by FRP composites, [1,2,3,4,5,6]. Almost all researchers studying in this field agree on the significant contribution of FRP jackets on strength and ductility of the concrete members with circular cross-section. However, there is not enough data available on the effect of FRP jackets for members with non-circular cross-sections, and the there is no consensus on the contribution FRP jackets to this type of members within the limited available data.

Although there are many research activities on this field all around the world, almost all of these studies are on medium and high strength concrete members. However, FRP jacketing may be a good solution for structural members that suffer from low concrete quality and lack of adequate confinement reinforcement. It is well known that, these two deficiencies are among the most common problems of existing reinforced concrete structures, particularly relatively older ones.

In the Structure Laboratories of Istanbul Technical University, an extensive research program, which also covers axial testing of FRP jacketed non-circular concrete members and members with low concrete compressive strength is under progress currently. In this paper, some of the experimental results for medium and low strength cylinder specimens are presented. The concrete compressive strength for medium strength specimens is around 30 MPa, and for low strength specimens around 6 MPa. For external confinement of specimens, varying thickness of carbon FRP sheets is utilized. More detailed information on these studies can be found elsewhere, [6,7]. It is well known that, carbon FRP composites have several advantages like higher strength and durability among other types of FRP composites like glass or aramid. It should also be noted that, carbon FRP composites are more expensive than the other composites mentioned.

2. Information on Tests

All the specimens are standard cylinders with the dimension of $150\,mm \times 300\,mm$. First and second sets of specimens have the unconfined concrete compressive strengths of 30 and 6 MPa, respectively. The concrete mix-proportions for each set are presented in Table 1. As seen in this table, water/cement rations for Set 1 and 2 are 0.43 and 1.27, respectively. In Set 1, super-plasticiser is used as admixture. In each set, two specimens are tested without any external confinement, and other specimens are tested after they are confined

Table 1
Mix-Proportions for Medium and Low Strength Concrete (kg/m^3).

Cement	Water	Sand	Stone Powder	Gravel No 1	Gravel No 2	Admixture	Total
420	180	450	400	750	200	4.2	2404
150	191	932	-	1074	-	-	2347

Table 2
Geometrical and Mechanical Properties of Composite Material.

Unit weight (kg/m^3)	1820
Effective cross-sectional area per unit width (mm^2/mm)	0.165
Tensile strength (MPa)	3430
Tensile elasticity modulus (GPa)	230
Maximum tensile deformation (mm/mm)	0.015

Table 3
Mechanical Properties of the Epoxy System.

Compressive strength (MPa)	80
Tensile strength (MPa)	50
Tensile elasticity modulus (MPa)	3000

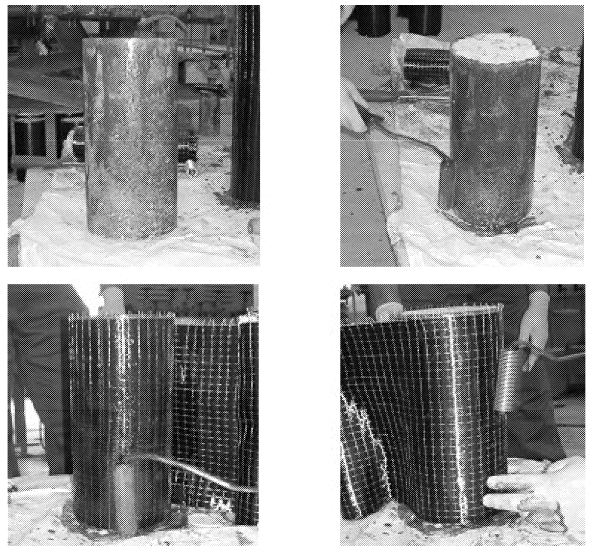

Figure 1. Steps of external confinement by FRP jackets

externally by 1, 3 or 5 plies of carbon FRP jackets in sets of 2. Some of the geometrical and mechanical properties of the unidirectional carbon FRP composite material, as provided by the manufacturer, are given in Table 2. It is known that the tensile stress-tensile strain relationship of carbon FRP composites is linear elastic up to failure.

During the preparation of carbon FRP jacketed specimens, layers of epoxy primer and putty are applied, then the composite sheets are bonded on the surface by epoxy adhesive, Fig. 1. Mechanical properties of the epoxy system, as given by the manufacturer, are presented in Table 3.

A schematical appearance of the externally confined specimens is presented in Fig. 2. As seen in this figure, composite material is wrapped at 0° angle with respect to the horizontal. For specimens that are wrapped with more than one ply, wrapping is carried out in a continuous manner. For all jacketed specimens, after the planned number of plies are bonded, the outermost ply is extended by an overlap of 150 mm. Test results in this study showed that 150 mm overlap length is enough for providing sufficient anchorage and preventing slippage between plies. According to the experimental results of Rochette and Labossiere [4], 100 mm overlap length is sufficient.

All specimens are tested until failure under concentric compression. A 5000 kN capacity Amsler compression machine is used for loading. The axial deformations are measured by the help of two displacement transducers over the entire height of the specimens and two strain gauges of 60 mm gauge length at mid-height. Transverse strains are also measured by two strain gauges of 60 mm gauge length at mid-height of the specimens. All data is recorded by a TML TDS-303 data logger. The test setup can be seen in Fig. 3.

The properties of the specimens included in this test program are given in Table 4, together with basic experimental data. In this table f'_c and f'_{cc} are the average unconfined and externally confined concrete compressive strengths, respectively, and ε_{cc} is the axial strain corresponding to confined compressive strength. NS and LS abbreviations represent normal strength and low strength concrete specimens.

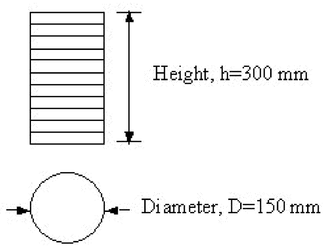

Figure 2. Schematical appearance of externally confined speciments

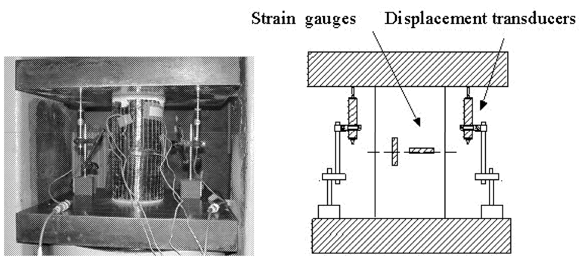

Figure 3. Appearance of testing setup

3. Test Results and Discussions

As seen in Table 4, the compressive strength and corresponding axial strain values increase significantly for both normal and low strength specimens, when they are jacketed with carbon FRP sheets. The increase in the jacket thickness, which is provided by increasing the number of FRP plies wrapped, significantly enhances compressive strength and deformability for two different levels of unconfined concrete compressive strength considered. The enhancements in compressive strength and corresponding axial strain are given quantitatively in Table 5. Note that, in this table, ε_{co} values, the axial strains corresponding to unconfined concrete compressive strength, are taken as 0.002 for both normal and low strength concrete.

The variations of average enhancements in strength and deformability are shown in Fig. 4. As seen in this figure, strength and deformability enhancements are much more significant for low strength concrete specimens. Consequently, the utilization of this strengthening technique is much more beneficial when the concrete compressive strength is relatively lower.

Before presenting experimental axial stress-axial strain relationships, a sample experimental data for Specimen LS-CYL-3-1 is given for showing the variations of measurements taken by displacement transducers and strain gauges, Fig. 5.

In Fig. 5, the vertical axis is the dimensionless stress, which is determined as the ratio of axial stress acting on the specimen at any time of loading (σ_c) to the unconfined concrete compressive strength (f'_{co}) of the same specimen. It can be understood from Fig. 5 that the readability limits of the strain gauges are below the axial strain that the specimens exhibit during tests. Additionally, Fig. 5 also shows that, the measurements taken for axial deformations by two vertical displacement transducers are almost same. Consequently, in the rest of this paper, the average axial strains determined by utilizing the measurements of two displacement transducers are taken into consideration during the presentations of axial stress-axial strain relationships.

The axial stress-axial strain relationships for normal and low strength specimens jacketed by 1, 3 and 5 plies of carbon FRP sheets are presented in Figs. 6 and 7, respectively. In these figures, axial stress-axial strain relationships of unconfined concrete specimens are also presented to provide a direct comparison of behavioral change more clearly. These figures indicate that, for both normal and low strength concrete, the axial stress-axial strain relationships change significantly in positive meaning. Especially for low strength concrete specimens, both compressive strength and corresponding axial strain increase tremendously.

As a result of this significant change in axial stress-axial strain relationships, it can clearly be stated that the strain energy also increases significantly for the carbon FRP composite jacketed specimens. To present a quantitative comparison, the strain energies are calculated by considering the areas under axial stress-axial strain relationships, Fig. 8. The calculated strain energy values are presented in Fig. 9. As seen in this figure, the increase in strain energy, which is a very good indicator for ductility, is very significant for FRP composite jacketed specimens of low and normal strength concrete specimens. It should be noted that, the increase in strain energy obtained for low strength concrete specimens is more than nor-

Table 4
Specimen Characteristics and Basic Experimental Data.

Specimen	Series	$f'_c(MPa)$	Number of plies	$f'_{cc}(MPa)$	ε_{cc}
CYL-0-90-average	NS	32.0	0	-	-
CYL-1-1	NS	32.0	1	48.5	0.013
CYL-1-2	NS	32.0	1	47.2	0.014
CYL-3-1	NS	32.0	3	83.8	0.034
CYL-3-2	NS	32.0	3	91.0	0.039
CYL-5-1	NS	32.0	5	107.1	0.050
CYL-5-2	NS	32.0	5	107.7	0.043
CYL-0-180-average	LS	6.2	0	-	-
CYL-1-1	LS	6.2	1	25.3	0.039
CYL-1-2	LS	6.2	1	19.4	0.026
CYL-3-1	LS	6.2	3	52.2	0.069
CYL-3-2	LS	6.2	3	56.9	0.075
CYL-5-1	LS	6.2	5	87.7	0.091
CYL-5-2	LS	6.2	5	82.7	0.094

Table 5
Quantitative Presentation of Enhancement in Strength and Deformability.

Specimen	Series	f'_{cc}/f'_c	$\varepsilon_{cc}/\varepsilon_{co}$
Average CYL-1-1 and CYL-1-2	NS	1.50	6.75
Average CYL-3-1 and CYL-3-2	NS	2.73	18.25
Average CYL-5-1 and CYL-5-2	NS	3.36	23.25
Average CYL-1-1 and CYL-1-2	LS	3.60	16.25
Average CYL-3-1 and CYL-3-2	LS	8.80	36.00
Average CYL-5-1 and CYL-5-2	LS	13.74	46.25

mal strength concrete specimens, when the increase relative to strain energies dissipated by unconfined specimens is considered, Figs. 6 and 7.

It should be noted that, although low strength specimens are tested under monotonic compression, normal strength specimens are tested under repeated compressive stresses with the exception of Specimen NS-CYL-1-1. However, İlki and Kumbasar [6] showed that the behavior of carbon FRP composite jacketed specimens is identical in the cases of monotonic and repeated compressive loads for the considered type of specimens. So, the envelopes of the axial stress-axial strain relationships are presented for the specimens that are tested under repeated compressive loads.

The failures of all specimens are due to sudden rupture of composite jackets. However, it should be stated that, for all carbon FRP composite jacketed specimens the failures are seen at very high levels of axial deformation, particularly

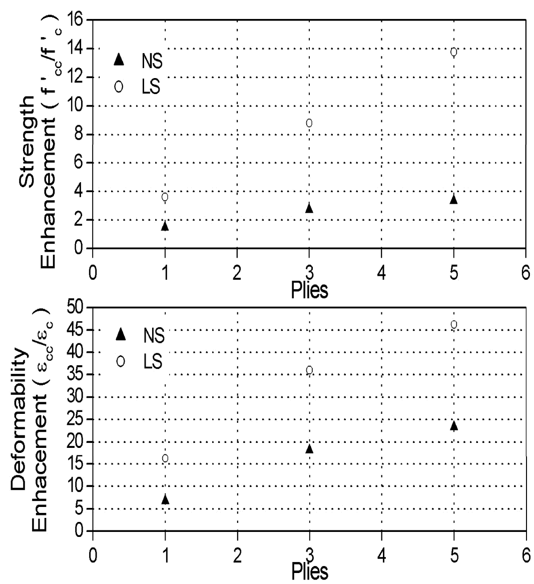

Figure 4. Variation of enhancements in compressive strength and corresponding strain for normal and low strength concrete speciments

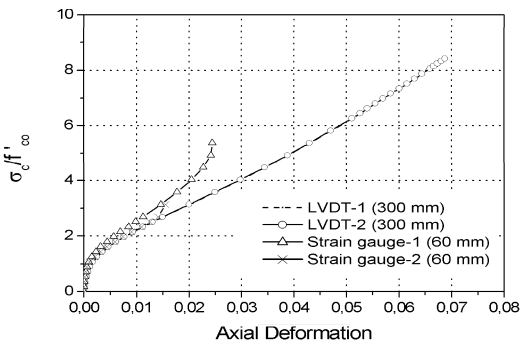

Figure 5. Variation of measurements by displacement transducers and strain gauges

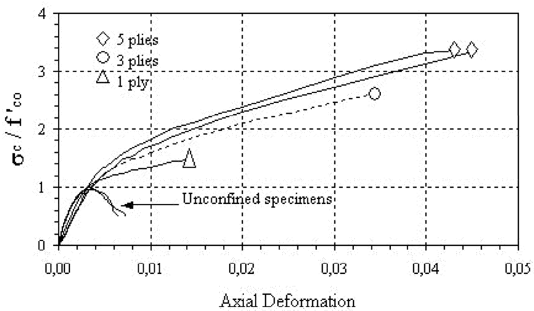

Figure 6. Axial stress-axial strain relationships for carbon FRP jacketed normal strength speciments, (NS)

for specimens with low unconfined concrete compressive strength.

4. Conclusions

At the end of the experimental study carried on 16 specimens, in order to determine the effects of carbon FRP composite jacket thickness and unconfined concrete compressive strength on the axial stress-axial strain behavior of concrete externally confined by carbon FRP sheets, the following conclusions are drawn.

The compressive strength, corresponding axial strain and ductility characteristics of concrete jacketed by carbon FRP composite sheets

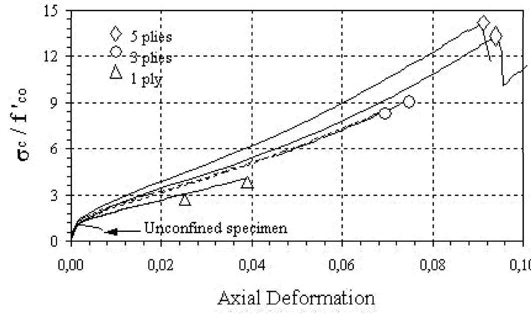

Figure 7. Axial stress-axial strain relationships for carbon FRP jacketed low strength speciments, (LS)

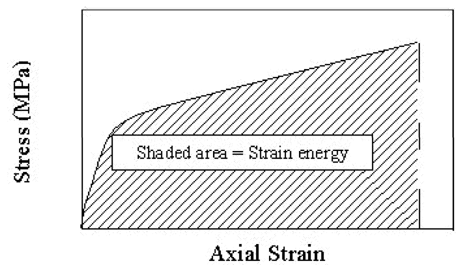

Figure 8. Area considered during calculation of strain energy

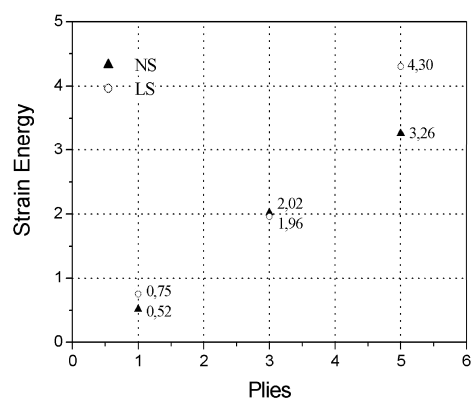

Figure 9. Areas under axial stress-strain relationships, (MPa)

improve significantly both for normal and low strength concrete specimens. When the thickness of the carbon FRP jacket is increased, the improvement on the axial stress-axial strain behavior becomes more significant. Both compressive strength and deformability enhancements are more pronounced for low strength concrete specimens. Due to improvement of strength and deformability, the strain energy is also increased significantly for all carbon FRP composite jacketed specimens.

Consequently, the investigated strengthening technique promises to be a good alternative for obtaining enhancement in axial strength and ductility of the structural members. Particularly, it is more promising for structural members with low concrete compressive strength and suffering from lack of adequate confinement reinforcement.

5. Acknowledgements

This study is financially supported by Istanbul Technical University Research Fund (1607), Turkish Earthquake Foundation (01-AP-118) and Yapkim Construction Chemicals Company. The assistance of Mr. Cem Demir and Mr. Aziz Karadeniz are also acknowledged.

References

[1] A. Mirmiran and M. Shahawy, ASCE Journal of Structural Engineering **123**, 583 (1997).

[2] V. M. Karbhari and Y. Gao, ASCE Journal of Materials in Civil Engineering **9**, 185 (1997).

[3] H. A. Toutanji, ACI Materials Journal **96**, 397, (1999).

[4] P. Rochette and P. Labossiere, ASCE Journal of Composites for Construction **4**, 129 (2000).

[5] Y. Xiao and H. Wu, ASCE Journal of Materials in Civil Engineering **12**, 139 (2000).

[6] A. İlki and N. Kumbasar, Int. Jour. Str. Eng. Mech. **13**, 75 (2002).

[7] A. İlki, N. Kumbasar, and V. Koç, Strength and Deformability of Low Strength Concrete Confined by Carbon Fiber Composite Sheets, Proc. 15th ASCE Engineering Mechanics Conference, New York (2002).