BEHAVIOUR OF CFRP REINFORCED LOW-STRENGTH CONCRETES SUBJECTED TO TEMPERATURE CHANGES AND SUSTAINED LOADS

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ABSTRACT :

After the catastrophic earthquakes in Turkey, it was realized that most of the concrete buildings at seismically active regions do not have adequate strength and ductility. In order to make those buildings survive during major earthquakes, they need to be seismically retrofitted. One alternative strengthening technique is the use of carbon fiber reinforced plastic (CFRP) wrapping technique. CFRP has a high tensile strength, a high modulus and is also light in weight and easy to handle. Although, CFRP applications are gaining popularity in seismic retrofitting, their long term behavior is still not very well known. While strengthening of the buildings with CFRP several layers of epoxy based adhesives are used. Those layers of materials as well as CFRP wrapped concrete may therefore be affected by different stress levels and environmental changes. In this study, the behavior of CFRP wrapped low strength (10 MPa) cylindrical concrete specimens (150x300 mm) are investigated when they are subjected to the compressive loads and temperature changes to determine the possible changes in strength and ductility. Sustained loads that are applied on cylinders are determined as the 40 % of their maximum strength. In addition to sustained loads, specimens are subjected to 200 temperature cycles, changing between -10°C to 50°C. In order to better understand the behavior of the CFRP wrapped concrete cylinders, specimens are divided in three groups. In each group mechanical characteristics are investigated to determine the effects of temperature changes, and sustained loads. This study presents the results of this ongoing project.

KEYWORDS: CFRP-strengthening, concrete, durability, long-term behavior, thermal effects

1. INTRODUCTION

Turkey is located in one of the most seismically active regions of the world, and after the two catastrophic earthquakes in the last decade; seismic retrofitting techniques are extensively utilized on existing reinforced concrete structures. Among various retrofitting techniques, use of carbon fiber reinforced plastics (CFRP) is the one that is becoming quite popular. In the literature there are various studies experimentally investigating the strength and strain capacity of cylindrical concrete columns with various strength levels wrapped with several layers of FRP. In such studies, it was found out that the use of FRP wrapping technique caused an increase in the capacity of concrete columns depending on the number of FRP plies applied, concrete grade, type of FRP and the properties of the matrix material (Lam et al. (2003), İlki et al. (2002), Samaan et al. (1998), Shahawy et al. (2000)). However, most of those experiments were conducted in the lab under room temperature.

In fact, reinforced concrete structures are often exposed to various environmental exposures with various deterioration mechanisms. When the deterioration of FRP reinforced concrete members are examined, several studies revealed that FRP wrapped concrete members could exhibit reduction in strength and strain capacities. Among those, Kshirsagar et al. (2000) tested 28 plain and 54 GFRP-wrapped concrete cylindrical specimens (102x204 mm) under environmental aging, and reported the reduction in confinement which also reduces the ultimate strength. Karbhari et al. (2000) and Karbhari (2002) tested standard size cylindrical concrete specimens under frost and freeze-thaw conditions. They also observed a reduction in compressive strength. Toutanji et al. (1998), (1999) tested CFRP and GFRP confined specimens under wet-dry and freeze-thaw conditions, and they reported little effect of wet-dry exposure on CFRP wrapped specimens, and a more pronounced reduction in strength on GFRP-wrapped specimens. On the other hand, they observed significant degradation on strength under freeze-thaw conditions. Saenz et al. (2006) tested FRP-confined cylindrical concrete specimens under several environmental exposures and reported a reduction in strength and axial strain capacities. Micelli et al. (2003) prepared an aggressive environment for standard concrete cylinders wrapped with CFRP and stated that in aggressive environments traditional metallic reinforcements were weak whereas CFRP reinforcement could be regarded as the durable structural solution in those environments. Kong (2005) and Kong et al. (2005) tested GFRP and CFRP confined light weight and normal weight cylindrical concrete specimens under freeze-thaw and/or sustained loading and they reported an average strength reduction of 3% under both sustained load and freeze-thaw exposure. Green et al. (2006) performed similar tests and reported a 2% reduction in CFRP-wrapped specimens and 9% reduction for GFRP-wrapped specimens when specimens are subjected to both freeze-thaw and sustained load.

Most of the abovementioned experiments were performed considering concrete grades above 20 MPa. However, in Turkey, the reinforced concrete structures that are being retrofitted have concrete grades much lower than that. Therefore, this study aims to evaluate the long-term environmental effect (sustained load and temperature cycles) on low strength concrete cylinders wrapped with one layer of CFRP.

2. MATERIALS AND TEST PROGRAM

2.1. Material Properties

In this experimental study, standard concrete cylinders with 150x300 mm in dimension were cast in our laboratory. Concrete target strength of 10 MPa was chosen representing a lower concrete grade. After uniaxial compression tests, the 28-day concrete strength was found to be 10.5 MPa. Moreover, carbon fiber reinforced polymer (CFRP) was used as the strengthening material. CFRP material had a tensile strength of 3430 MPa, an elasticity modulus of 230 GPa and an ultimate strain of 1.5% all in the fiber direction as specified by the manufacturer.

2.2. Specimen Preparation

Cylindrical concrete specimens were either wrapped with one layer of CFRP using a wet lay-up process or left unwrapped. The wet lay-up process as depicted in Figure 1 composed of:

- Cleaning - the surface of the cylinders were cleaned that can prevent full bond between concrete and CFRP,
- Primer layer - a thin layer of primer was applied and specimens were cured for a day,
- Putty layer - putty layer was applied on the primer layer in order to create a smooth surface between concrete and CFRP,
- Epoxy layer - CFRP sheets were cut in a desired length and then epoxy was applied on concrete and CFRP,
- CFRP wrapping - finally concrete was wrapped with CFRP providing 30 mm (6.4 % of the perimeter of the cylinder) and 50 mm (10.6 % of the perimeter of the cylinder) overlapping.

(a) Specimen with primer layer (b) Specimen with putty layer (c) CFRP wrapped specimen

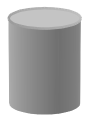
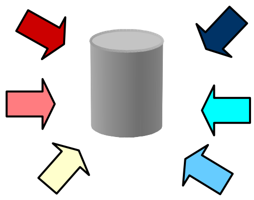
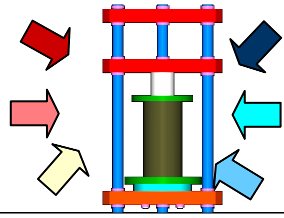
Figure 1: Wet lay-up process

During the wrapping process of the specimens, care was taken to eliminate the voids between concrete and CFRP. The reason for supplying relatively short overlapping is to simulate one layer strengthening without introducing lengthy stiff parts. For that reason, the overlapping region was kept less than 11% of the perimeter, and it was assumed that concrete will exhibit the same confining stress around its circumference.

2.3. Test Program

The cylindrical specimens prepared in our laboratory were tested in three groups as shown in Table 1. First group of specimens were kept under room temperature as control specimens. Second group of specimens were exposed to only temperature cycles without any sustained loads. Finally, the last group of specimens was loaded to 40 % of their ultimate strength, while simultaneously exhibiting temperature cycles. It should also be mentioned that in addition to CFRP-wrapped specimens each group contained unconfined specimens.

Table 1: Test procedure and specimen groups

Group 1: No load no temperature effect	**Group 2:** No load but temperature effect	**Group 3:** Load and temperature effect
		

Temperature cycles were applied using an environmental test chamber. As shown in Figure 2, each cycle consisted of heating and cooling periods. The heating cycle consisted of increasing the room temperature to 50°C and maintaining the temperature at that level for 30 min. The heating period is later followed by a cooling period, in which the room temperature is dropped down to -10°C. The specimens were subjected to this freezing temperature for an hour. Therefore, a typical cycle approximately lasted for 9 h 30 min. The specimens were subjected to a total of 200 temperature cycles. Moreover, in order to keep the sustained load on the specimens, special loading frames were designed and built as shown in Figure 3a, and the load on each specimen were monitored continuously via a data acquisition system integrated to the environmental test chamber shown in Figure 3b.

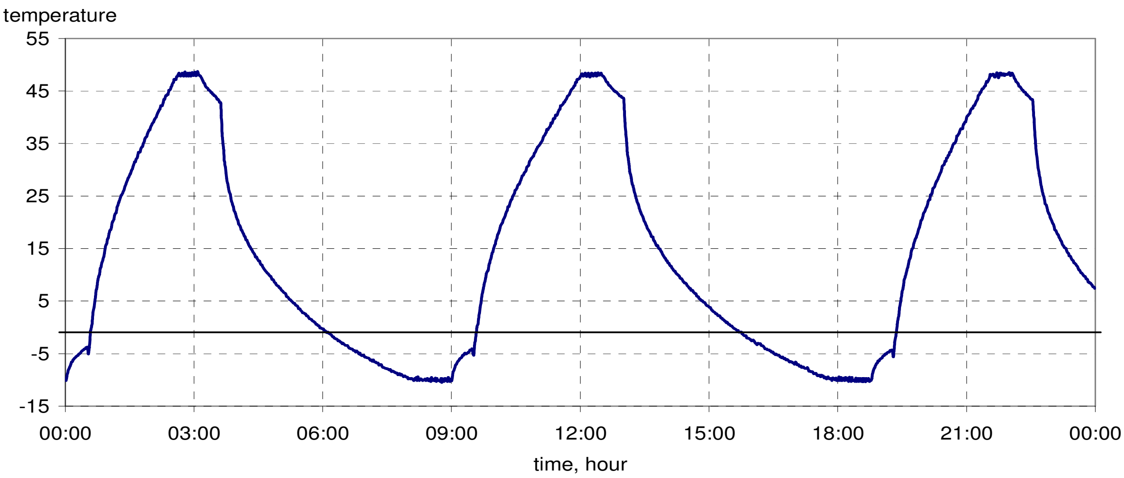


Figure 2: Typical temperature cycles

(a) Specially designed loading frame

(b)Environmental test chamber

Figure 3: Experimental test set-up

3. RESULTS AND DISCUSSIONS

In order to understand the effects of sustained loads and/or temperature cycles on the mechanical properties of CFRP wrapping, all specimens were tested under compressive load until failure and stress-strain diagrams were plotted using the test setup proposed in ASTM C469-02.

3.1. Reference Specimens (Specimens of Group 1)

As previously stated, Group 1 specimens were kept as control specimens under room temperature. Axial stress-axial strain diagrams of both confined (CFRP wrapped) and unconfined specimens are presented in Figure 4.

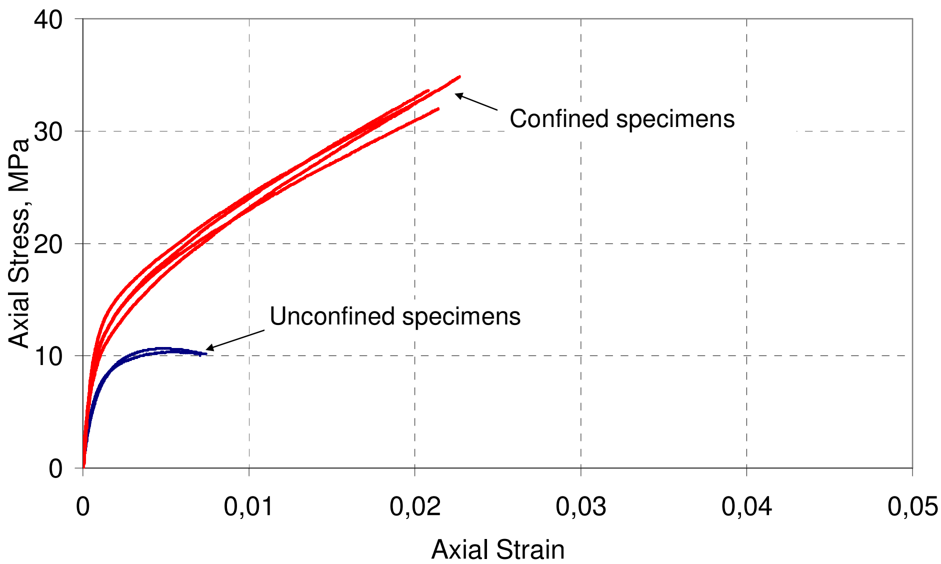


Figure 4: Axial stress-axial strain diagrams of Group 1 specimens

Table 2: Mechanical properties of confined and unconfined Group 1 specimens

Property of the specimen	Max. Strength, MPa	Strain corresponding to max. strength	Modulus of Elasticity, GPa
Confined	33.5	0.0215	19.7
Unconfined	10.5	0.0047	11.0
Difference (Confined/Unconfined)	3.2	4.6	1.8

In Figure 4, it is seen that stress-strain diagram of a typical CFRP confined concrete shows almost a bilinear response. Since CFRP is ineffective at small strain values the first portion of the diagram is mainly controlled by concrete. However, the second portion of the diagram is characterized by CFRP. The transition zone between the two slopes indicates when the FRP wrapping effectively begins to restrain the lateral dilation of concrete (Shahawy (2000)). CFRP material oriented in hoop direction, i.e. strong in that direction, can limit this expansion up to its strain capacity. As it is seen from Figure 5 confined concrete fails due to CFRP rupture at mid-height since lateral expansion, thus higher tensile stresses develop at that location. As it is revealed in Table 2, single layer CFRP increases the low grade concrete strength to approximately 3 times and the strain corresponding to that strength up to 5 times.

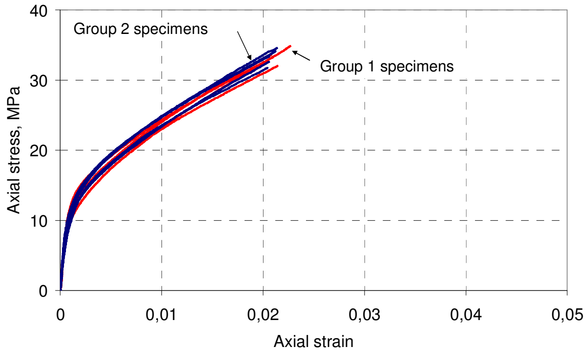
Figure 5: Typical views of low-stregnth concrete specimens after compressive strength tests

3.2. Specimens Exposed to Temperature Cycles (Group 2 specimens)

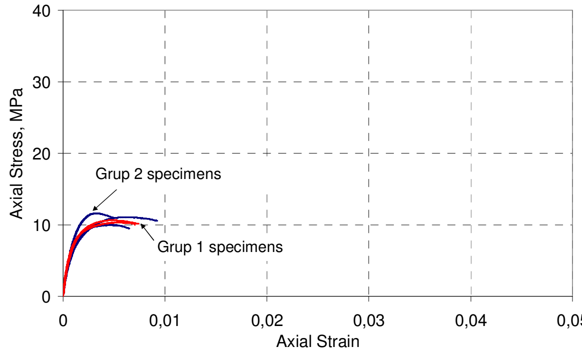
In this group, specimens were kept in an environmental test chamber while exhibiting 200 temperature cycles. Table 3 and Figure 6 present the mechanical properties and the axial stress-axial strain diagrams of Group 1 and Group 2 specimens comparatively. In the table f'_{cc} stands for confined concrete strength, ε_{ult} for ultimate strain corresponding to f'_{cc}, f'_{co} for unconfined concrete strength, ε_{co} for strain corresponding to f'_{co} and E for secant modulus of elasticity as determined from 40% of unconfined concrete strength. As shown in Figure 6 and Table 3, confined specimens were almost not affected by temperature cycles. The effects can only be seen in terms of strain as stated also by Kong (2005) and Kong et al. (2005) and to a certain extent on modulus of elasticity.

Table 3: Properties of confined Group 1 and Group 2 specimens

Test Group	a) Confined			b) Unconfined		
	f'_{cc}, MPa	ε_{ult}	E, GPa	f'_{co} MPa	ε_{co}	E, GPa
Group 1	33.5	0.0215	19.7	10.5	0.0047	11.0
Group 2	33.3	0.0208	19.4	10.9	0.0041	9.4
Difference, %	-0.6	-3.1	-1.2	3.7	-12.3	-14.7



a) Confined specimens



b) Unconfined specimens

Figure 6: Comparative axial stress-axial strain diagrams of Group 1 and Group 2 specimens

3.3. Specimens Exposed to Temperature Cycles and Sustained Loads (Group 3 specimens)

As the aim of this study is to determine how mechanical properties of a CFRP reinforced concrete specimen are affected by sustained loads while simultaneously exhibiting temperature cycles, specimens were subjected to both mechanical and environmental loads. In order to conduct tests, low-strength specimens CFRP wrapped with 30 mm of overlap were prepared. Those specimens were loaded approximately 40% of their ultimate strength and load was kept constant in the environmental chamber. However, two of those specimens failed due to delamination of CFRP after 42 cycles (Figure 7). Failures were attributed to the insufficient bond, so three additional specimens were re-prepared by giving care to the bond location. Those specimens again failed due to delamination without even reaching 40 temperature cycles. Therefore, it was concluded that providing an overlap of 30 mm was not sufficient and the bond length should be increased.

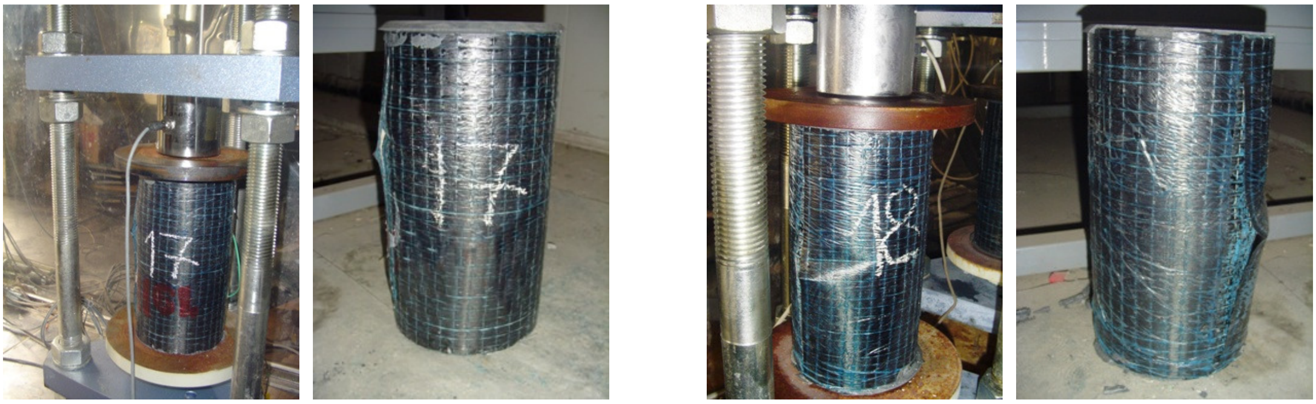
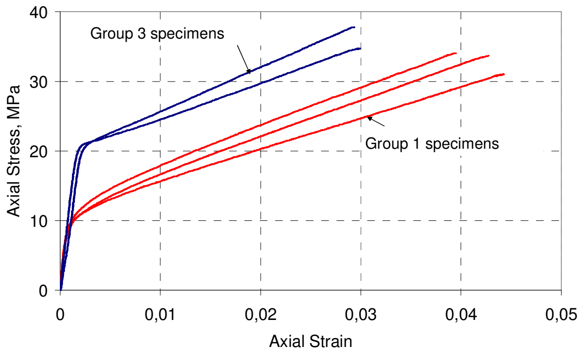


Figure 7. Delamination of CFRP wrapped specimens with a 30 mm overlap

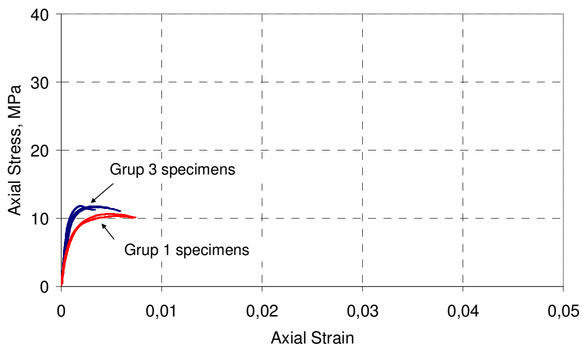
Having concluded on the inadequacy of the overlap length, new specimens for all groups having 10 MPa strength were prepared with 50 mm overlap (10.6 % of perimeter of cylinder) and subjected to the same conditions. This time, providing 10.6 % overlap was effective as all specimens survived 200 temperature cycles. After reaching the desired number of temperature cycles, specimens were loaded to failure and the axial stress-axial strain diagrams were obtained as shown in Figure 8. As seen from that figure, concrete gained strength when simultaneously exhibiting sustained loads and temperature cycles. However, its strain capacity reduces and concrete seemed to be more brittle.

It is seen from Figure 8a that for confined specimens, transition zone between first portion and second portion of the diagram increases. This can be attributed to the fact that unconfined concrete strength which is the dominant material of the first portion of the diagram, increases when subjected to sustained loads and temperature changes.

However, since second portion is controlled by CFRP material no strength difference was observed afterwards. As it is seen from Table 4 for Group 3 specimens the ultimate strain decreases whereas the maximum strength increases as compared to control specimens.



a) Confined specimens (Overlap 50 mm)



b) Unconfined specimens

Figure 8: Effect of sustained load and temperature cycles on stress-strain behavior of specimens

Table 4: Effect of sustained load and temperature cycles on stress-strain behavior of specimens.

Test Group	a) Confined specimens (Overlap 50 mm)			b) Unconfined specimens		
	f'_{cc}, MPa	ε_{ult}	E, MPa	f'_{co}, MPa	ε_{co}	E, MPa
Group 1	32.4	0.0436	18.1	10.5	0.0047	11.0
Group 3	36.3	0.0297	11.4	11.7	0.0026	14.6
Difference, %	12	-31,9	-37	11.9	-44.9	32.9

4. CONCLUSIONS

As a result of this ongoing experimental research program carried out at the METU Civil Engineering Department located in Ankara-Turkey following preliminary conclusions are obtained:

- Single layer of CFRP wrapping increases strength of low strength concrete 3 times and strain 5 times.
- The mechanical properties of both confined and unconfined specimens were almost not affected by the 200 temperature cycles alone.
- When unconfined concrete specimens are loaded while simultaneously subjected to temperature cycles, they become more brittle and rigid because they gain strength and lose strain under this condition.
- Supplying an overlap of 6.4 % of the perimeter of cylindrical specimen seemed to be insufficient when those specimens are exposed to both sustained load and temperature cycles.
- Confined and unconfined concrete specimens exhibit strength increase, but strain decrease when exposed to temperature cycles and sustained loads.

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