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The Effect of Elevated Temperatures on the Tensile Strength of CFRP Bars with a Cladding Layer

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Abstract
This paper presents results from an experimental study on the effect of temperature on tensile strength of carbon fiber-reinforced polymer (CFRP) bars with a cladding layer in 20–600 °C temperature range. The experiments included the tests both at elevated temperatures and after elevated temperatures. The results indicate when the temperature is up to T_g (glass transition temperature of the resin), the strength of CFRP bars begin to deteriorate. However, after cooling to ambient temperature, the strength of the loss can be largely restored. When the temperature is up to T_d (decomposition temperature of the resin), CFRP bars are irreparably damaged. Besides, the cladding layer has an oxygen isolation effect. When the advantage of oxygen isolation is used, the residual strength of CFRP bars can be significantly improved.

Keywords: CFRP; High temperature; Mechanical properties; Short basalt fibers; Inorganic mortar

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1. Introduction

In recent years, fiber-reinforced polymer (FRP) reinforcements are widely used in new buildings or strengthening of reinforced concrete structures for their high-strength, light-weight, and anti-corrosive qualities. In many applications, provision of appropriate fire resistance is one of the major design requirements.
In order to study the degradation of mechanical properties of FRP materials at high temperatures, many scholars have made efforts, including many experimental studies and many prediction models [1,2,3,4]. However, all their experimental studies are carried out by exposing FRP bars directly to elevated temperatures. The FRP bars are covered by protective layer in FRP reinforced concrete members and covered with filling materials in near-surface mounted (NSM) FRP strengthened structural members, indicating FRP bars are not directly exposed to the air. Therefore, some improvements need to be considered.
In this paper, CFRP bars were covered with a cladding layer to avoid exposing CFRP bars directly to air. Then CFRP bars with a cladding layer were exposed to different high temperatures. The tensile properties of them will also be studied at elevated temperatures and after high temperatures. The results will also be compared with previous studies.

2. Experimental program

The experiments consisted of 46 CFRP bars with a cladding layer. 18 of them were tested at different elevated temperatures, while the remaining 28 were tested after different high temperatures. The diameter and length of CFRP bars with the vinyl ester (T_g was about 120 degrees) were 10mm and 1200mm, respectively. The nominal tensile strength and modulus of CFRP bars, tested at ambient temperature, is 1970 MPa and 150 GPa, respectively.
Before casting the cladding layer, a K-type thermocouple was fixed in the middle of CFRP bars. The cladding layer was a kind of mortar mixed with short basalt fibers. The water-cement ratio was 1:2, the cement-sand ratio was 1:3 and 10.86g of short basalt fibers were mixed in a cladding layer. This composition ratio confirmed the best cracking resistance for the cladding layer from the previous studies of our group. The detailed size of a cladding layer was shown in figure 1. This size was designed according to the internal size of the high-temperature electric furnace. Also, 25mm thick cladding layer for CFRP bars could be guaranteed at the central part of the specimen because 25mm is the minimum concrete cover thickness in the Chinese code.

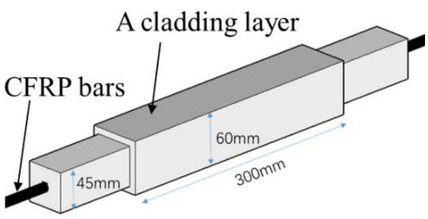

Figure 1: Schematic diagram of a cladding layer

After 28 days of maintenance, CFRP bars were inserted into steel pipes, and then adhesive was injected into the pipe. The nominal dimensions of steel pipes are 22 mm in outer diameter and 3 mm in thickness, and the pipes were cut into tubes of 300 mm length by referencing the ACI 440.3 standard and previous studies [1,2].
There were six high-temperature conditions. To stimulate the real fire condition, the heating

rate was 100 degrees per minute until the furnace reached the targeted temperatures. When the internal CFRP bar was heated to a targeted temperature, the heating was continued for another one hour. The high-temperature furnace is showed in figure 2 and figure 3 shows the heating curves. The solid lines in figure 3 mean the temperatures tested in the furnace and the dotted lines mean the surface temperature of CFRP bars at different elevated temperatures. Experiments tested at elevated temperatures were immediately carried out after another one-hour heating. For experiments tested after high temperatures, the specimen should be cooled down to ambient temperature naturally after additional 1h heating. Then the cladding layer was removed carefully, and the internal CFRP bars were taken out to carry out a tensile test. The loading rate was 2mm/min.

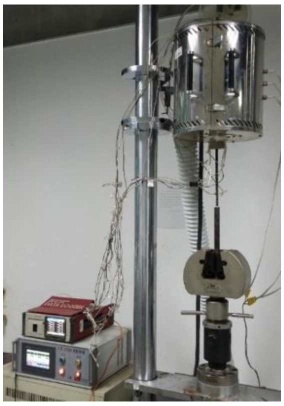

Figure 2: Test set-up

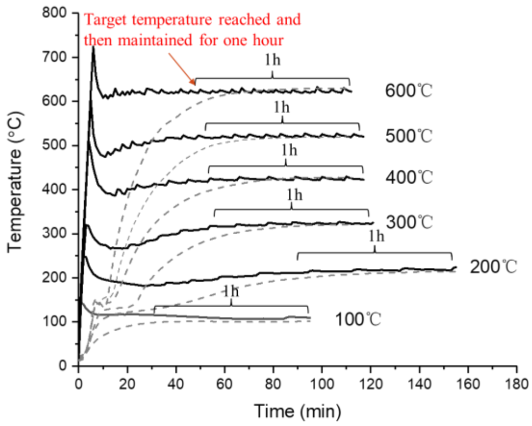

Figure 3: Heating curves

3. Results and Discussion

After the prescribed heating time at different high temperatures, the cladding layer maintained good integrity, indicating the great cracking resistance. After the tension test, the cladding layer was removed and the failure modes of CFRP bars are shown in figure 4. When temperatures are below 300 degrees, CFRP bars split into fiber bunches, and then fibers get fractured around the mid-part. The failure mode shows the decomposition of a small part of resin at 400 degrees. At 500 degrees, little resin left and fibers are stretched apart. When the temperature is up to 600 degrees, fibers get separated because of no resin left. All specimens are stretched apart around the middle, indicating the reasonable failure mode and the tested strengths are reliable. The failure modes of CFRP bars at elevated temperatures and after elevated temperatures are the same. So, it can be concluded that the decomposition of resin begins at around 400 degrees.

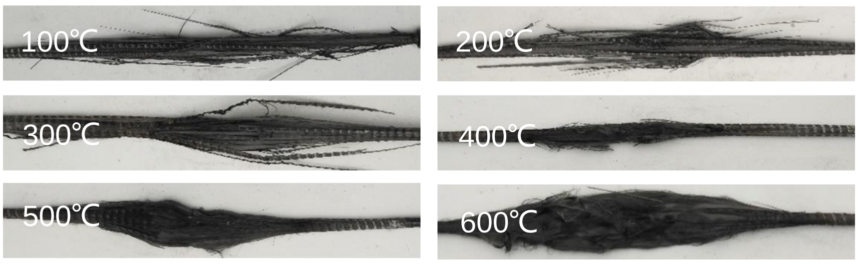

Figure 4: Failure modes of CFRP bars at different high temperatures

The normalized tensile strength of CFRP both at elevated temperatures and after elevated temperatures are shown in figure 5. Besides, some results of previous studies only about CFRP bars are also added in figure 5 to facilitate comparison. In previous studies, the heating rate of 5-10 degrees per minute was taken. After reaching the targeted temperature, it would last only for 20-30 minutes, indicating the high-temperature environment in this paper is much worse. The legend in figure 5 illustrates the diameter of CFRP bars in different literature.

From figure 5, some distinct characteristics can be found: (1) For experiments tested at elevated temperatures, the strength of CFRP bars with a cladding layer at 100 degrees is close to that at ambient temperature. When the high temperature is up to 200 degrees (above T_g), the strength drops significantly. Then the strength decreases further at 400 degrees (above T_d). Finally, the strength at 600 degrees is 35.4% of that at ambient temperature. (2) For experiments tested after elevated temperatures, the results show the different characteristic. After 300 degrees (below T_d) elevated temperature, CFRP bars with a cladding layer can retain above 90% of initial strength at ambient temperature. However, the strength deteriorates significantly after 400 degrees. Finally, the strength after 600 degrees is 39.5% of that at ambient temperature. (3) The residual tensile strength after different elevated temperatures is higher than that at different elevated temperatures. However, the strength is similar both at elevated temperatures and after elevated temperatures when the temperature is above 400 degrees. (4) The residual tensile strength at elevated temperatures in this paper is slightly higher than that in other literature from room temperature to 300 degrees. However, the residual strength with a cladding layer is much higher when high temperature is up to 400 degrees.

Some reasons can be accounted for the above characteristics: (1) When CFRP bars are exposed to high temperatures directly, softening of the resin causes the strength of CFRP bars to decrease. However, for experiments tested after elevated temperatures, the resin will solidify again after cooling and most of the strength will recover. Decomposition of the resin causes fibers to lose protection. Then, the strength of fibers is damaged due to fiber oxidation, leading to a large decrease in the strength of CFRP bars. (2) When CFRP bars are covered with a cladding layer, the cladding layer will act as an oxygen barrier, which will prevent fibers from being oxidized. After decomposition of the resin, CFRP bars are stratified along the longitudinal direction. Then, external fibers and internal fibers cannot work together, also leading to a decrease in the strength of CFRP bars. However, the residual strength of CFRP bars can be significantly improved because of the oxygen barrier provided by the cladding layer.

4. Conclusions

(1) When the high temperature is up to T_g of resin, the resin begins to soften, indicating the strength of CFRP bars begins to deteriorate. However, the strength of CFRP bars can recover after cooling to ambient temperature, because the resin does not decompose.

(2) CFRP bars with a cladding layer at 600 degrees and after 600 degrees can retain 35.4% and 39.5% of initial strength at ambient temperature respectively. Both residual strengths are similar, indicating the damage caused by the decomposition of resin is irreversible. The decomposition of the resin prevents external fibers and internal fibers from working together, which has a bad impact on the strength of CFRP bars.

(3) Compared with results from other literature, the residual strength of CFRP bars with a cladding layer has been significantly improved because of the effect of the cladding layer. The oxidation of fibers influences the strength of fibers, but the cladding layer has an oxygen isolation effect that prevents fibers from being oxidized, which should be taken into consideration in structural design.

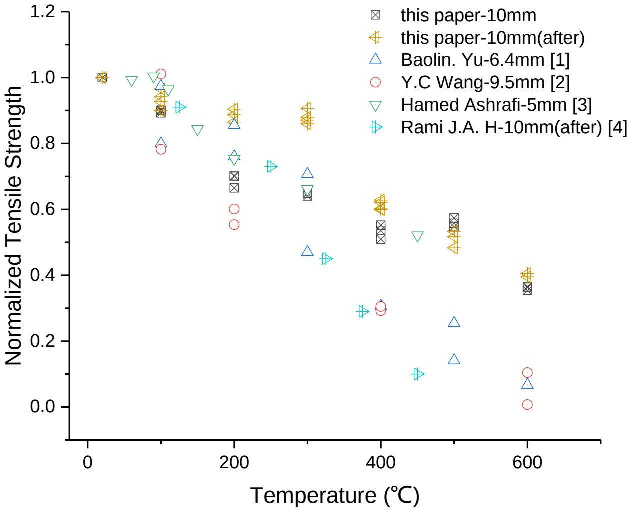

Figure 5: Results of residual tensile strength

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