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Effect of using carbon nanotube modified epoxy on bond–slip behavior between concrete and FRP sheets

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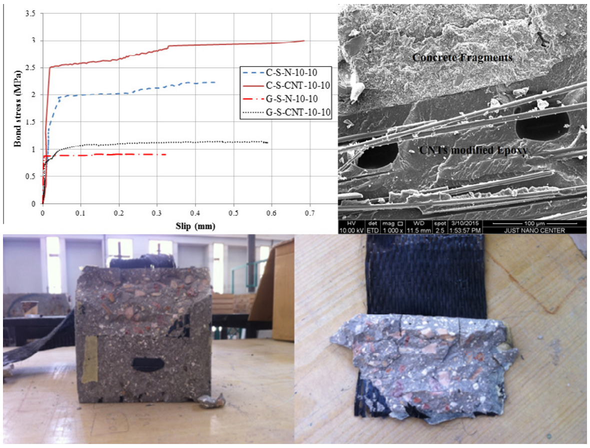
HIGHLIGHTS

- Bond–slip behavior between concrete and FRP composites was improved using CNT.
- Using CNT modified epoxy enhanced both bond strength and ultimate slippage.
- Bond enhancement between FRP and concrete depends on fiber and epoxy type and bond area.
- SEM images showed that CNTs could improve the adhesion at the FRP/concrete interface.

GRAPHICAL ABSTRACT



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ABSTRACT

The influence of carbon nanotubes (CNTs) on the bond–slip behavior between concrete surfaces and fiber-reinforced polymer (FRP) sheets was investigated. A total of 30 concrete prisms were casted, reinforced with FRP sheets, and tested under double-shear test. Carbon or glass FRP sheet strips with different lengths and widths were externally bonded to the concrete prisms using either neat or CNT modified epoxy. The effects of epoxy type, fiber sheet type, FRP bond length, and FRP bond width on the bond behavior were investigated through the failure mode, bond stress versus slip curves, and scanning electron microscopy (SEM) imaging. Experimental results showed that using CNT modified epoxy resin enhanced the bond strength and ultimate slippage of the tested specimens. The enhancement was highly dependent on the type of epoxy and fiber sheet. The bond behavior between concrete surface and FRP was affected by bond length and width. Scanning electron microscope images showed that CNTs could improve the adhesion at the carbon fiber/epoxy interface and concrete/epoxy interface leading to improvement in the load transfer and bond strength.

1. Introduction

Recently, fiber-reinforced polymer (FRP) has been widely used in strengthening of concrete structures due to several reasons such as high strength to weight ratio, high corrosion resistance, and ease

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of installation [1–10]. However, the effectiveness of this technique highly depends on the bond behavior at the interface between the FRP and the concrete. Many studies showed that de-bonding between FRP and concrete represents the major failure mode of FRP-strengthened concrete structures [11–13]. Thus, the ultimate performance of the retrofitting system is associated with the interfacial bonding between FRP sheet and concrete. For the last two decades, many studies investigated the bond behavior at the interface between the FRP and the concrete. It was reported that the interfacial bond behavior of the FRP and concrete depends on many factors such as concrete strength, surface roughness, FRP strength, FRP bond length and width, and adhesive strength and stiffness [11,13–26].

On the other hand, epoxy resin is the most commonly used polymer matrix to impregnate the fiber sheet and bond them to the concrete surface. The properties of this adhesive is very crucial in determination the FRP–concrete bond strength. Herein, we are looking at enhancing the properties of the epoxy matrix by proper incorporation of nanomaterials such as CNTs. These high aspect ratio nanofillers are considered the most promising nano-reinforcements owning to their outstanding properties. Many studies have shown that adding CNTs into epoxy improves its flexural strength [27], tensile strength [28,29], toughness [27,29], young modulus [27,28,30], and fracture strain [28]. Moreover, using CNT modified epoxy resin along with carbon fiber to produce hybrid composites has attracted significant attention in recent years. A host of studies showed that adding CNTs into epoxy and using it with carbon fiber caused an improvement in the composites fracture toughness [31–33], flexural strength and modulus [34], interfacial shear strength [35–38], and the interfacial adhesion between epoxy matrix and carbon fiber [36,37,39]. But, limited studies were directed toward using these nanocomposites in construction applications. Recently, we have investigated the effectiveness of using CNTs to enhance the strengthening efficiency of RC columns and beams using carbon fiber/epoxy composites. The results showed that modifying the epoxy resin with CNTs can improve the load carrying capacity of RC columns and the flexural resistance of RC beams [40]. Rousakis et al. [41] studied the effectiveness of using CNT modified epoxy for confinement of concrete columns using glass fiber sheet. Their results showed that the bearing load of confined concrete specimen was enhanced in the case of using CNT modified epoxy.

The objective of the current study is to investigate the efficiency of using CNTs to enhance the bond–slip behavior of FRP–concrete interfaces. A total of 30 concrete blocks (150 × 150 × 100 mm) were prepared then bonded to FRP sheets using neat or CNTs modifies epoxy. Pull-off testing of double-shear bond specimens was carried out to establish bond stress–slip relationship using a special fixture attached to a universal testing machine. Scanning electron microscopy (SEM) was used to investigate the microstructure of fracture surfaces. The effect of fiber type, epoxy type, and fiber bond length and width on the CNTs modification was studied.

2. Experimental program

2.1. Test specimens

A total of 30 concrete prisms with dimensions of 150 × 150 × 100 mm were casted. FRP sheet strips with different types, lengths, and widths were then externally bonded to two opposite sides of the prisms using either neat or CNT modified epoxy. General layout of test specimens is shown in Fig. 1. A total of 10 different FRP systems were tested. Specimens' designation and summary of test program are summarized in Table 1.

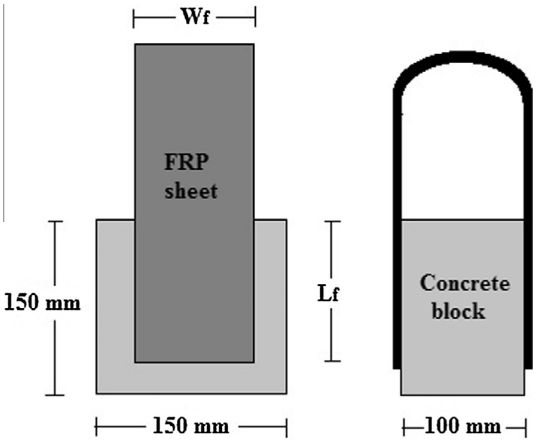

Fig. 1. Configuration of test specimens.

2.2. Material properties

A concrete with 28-days compressive strength of 34 MPa was used in this study. To obtain the proposed strength, 505 kg/m^3 Type I Ordinary Portland cement, 830 kg/m^3 crushed coarse limestone aggregates with a maximum size of 12.5 mm, 110 kg/m^3 silica sands, and 440 kg/m^3 crushed fine limestone were used to prepare the concrete mix following ACI 211 mix design procedure as shown in Table 2. A water/cement (w/c) ratio of 0.47 was used. Two different types of fiber sheet were used in this study: carbon fiber (MBrace CF 230/4900, BASF, Germany) and glass fiber (MBrace GF 73/3400, BASF, Germany). Two different types of epoxy resin were used: MBrace Saturant (BASF, Germany) and Sikadur 330 (Sika, Switzerland). These epoxy systems composed of two parts: Part A is the neat epoxy and Part B is the hardener (curing agent). Type I epoxy (Sikadur 300) is characterized by high viscosity and good adhesion, while Type II epoxy (MBrace Saturant) is characterized by low viscosity and good adhesion. The main properties of fibers and epoxy systems are summarized in Tables 3 and 4, respectively. A master-batch of CNT reinforced epoxy (EpoCyl™ NC R128-02, Nanocyl, Belgium) was used as a source of CNTs. This master-batch is based on liquid Bisphenol-A epoxy resin and contain 20 wt% of NC7000 multi-walled CNT (Nanocyl, Belgium). These nanotubes are 1.5 µm in length and 9.5 nm in diameter as shown in Table 5.

2.3. Preparation of CNT modified epoxy

The CNT modified epoxy was prepared according to the recommendations of the manufacturer. The dispersion was performed by adding 221 g of the CNT master-batch to 779 g of neat epoxy (Part A of the epoxy). The mixture was mechanically stirred for 5 min using magnetic stirrer then it was sonicated in ultra Sonicator (Q700, Qsonica, LLC, USA) for 30 min. After that, the hardener (Part B of the epoxy) was added (30 g hardener/100 g resin) and the whole mixture was mixed using a low speed mixer at 600 rpm for 4 min. Based on the concentration of the CNTs in the master-batch and the added amount of epoxy (Part A and Part B), the concentration of CNTs in the modified epoxy was 3.4 wt%. This concentration was calculated as follows:

$$\text{wt\% CNT} = \frac{0.2 \times \text{CNT master-batch}}{\text{CNT master-batch} + \text{Part A epoxy} + \text{Part B epoxy}}$$

$$\text{wt\% CNT} = \frac{0.2 \times 221\ \text{g}}{221\ \text{g} + 779\ \text{g} + 233.7\ \text{g}} = 0.034 = 3.4\%$$

2.4. Specimen preparation and test setup

Concrete blocks were cast into special wooden forms. Twenty-four hours after casting, the test specimens were de-molded and then wet-cured for 28 days. Afterwards, weak layers of concrete were removed and the surface of the specimens was leveled. For better bonding, the concrete surfaces were then getting rough using diamond grinding disk and cleaned using vacuum cleaner. After that, the fiber sheets were cut into desired sizes and were adhered to concrete prisms using epoxy resin according to the following procedure: A layer of epoxy or CNT modified epoxy was spread uniformly over the desired area of concrete prism. The fiber sheet was then placed onto the resin and rolled by a plastic roller until the resin was distributed over the whole fiber surface and penetrate through fiber strands. Finally, a second layer of epoxy or CNT modified epoxy was painted over the fiber sheet surface. The specimens were then left under room condition for one week before testing. The first 25 mm of the FRP was left un-bonded to eliminate the stress concentration. All of the specimens were subjected to double-shear test using a universal testing machine as shown in Fig. 2. The test was conducted under displacement control with a rate of 0.3 mm/min. Two linear variable displacement transducers (LVDT) were used to record the slip at both sides of the specimens. To make sure that the relative displacement between CFRP and concrete was monitor, the LVDTs were placed in such a way to connect between two points, one point located on the top of CFRP and another point located on the concrete surfaces. The