Composite Structures 184 (2018) 1–10

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Mechanical behavior of ultra-high toughness cementitious composite strengthened with Fiber Reinforced Polymer grid

Yu-Zhou Zheng[a,b,c], Wen-Wei Wang[a,*], Khalid M. Mosalam[b,c,*], Zhong-Feng Zhu[a]

[a] Department of Bridge Engineering, School of Transportation, Southeast University, Nanjing, China
[b] Department of Civil and Environmental Engineering, University of California, Berkeley, CA, USA
[c] Pacific Earthquake Engineering Research (PEER) Center, University of California, Berkeley, CA, USA

ARTICLE INFO

Keywords:
BFRP grid
Strengthening
Stress–strain relationship
Tensile force capacity
Tensile test
UHTCC

ABSTRACT

A new strengthening composite system, namely Basalt Fiber Reinforced Polymer (BFRP) grid – Ultra-High Toughness Cementitious Composite (UHTCC) for Reinforced Concrete (RC) structures is explored in this paper. Thirty UHTCC specimens internally strengthened with BFRP grid and six similar reference specimens without strengthening were tested to investigate the tensile mechanical behavior. The reinforcement ratio of the BFRP grid (0.17%, 0.68%, and 1.16%) and the mix proportion of the UHTCC were the two main test parameters. The experimental results highlighted two failure modes: 1) rupture or slip off failure of chopped PolyVinyl Alcohol (PVA) fibers at the critical crack sections in the reference specimens, and 2) partial rupture failure of BFRP grid within the UHTCC in all strengthened specimens. Moreover, the relative slip at the interface between the BFRP grid and the UHTCC substrate was not observed during testing. The tensile force capacity of the strengthened BFRP–UHTCC specimens increased by 42% to 172% compared to the reference specimens depending on the reinforcement ratio of the BFRP grid. On the other hand, the tensile force capacity of BFRP–UHTCC specimens slightly decreased by 1% to 14% with the increase of the water-to-cement material ratio of the UHTCC layer from 24% to 38%. Additionally, a stress–strain relationship and strength models of the strengthened specimens are proposed and verified with the test results to predict the tensile mechanical behavior.

1. Introduction

With the wide application of Fiber Reinforced Polymer (FRP) composite in strengthening Reinforced Concrete (RC) structures, a few of potential drawbacks have been presented by some researchers when using the Epoxy resin as the bonding and impregnated agent [1–5]. These drawbacks include debonding of interface, rapid aging, poor resistance to fire and ultraviolet (UV) light, etc [6]. In order to overcome such drawbacks, some researchers attempted to replace the organic matrix composite (e.g. Epoxy resin) with inorganic or cementitious materials to develop relatively new fiber composite reinforcing systems for strengthening RC structures. Examples of such attempts include Polymer Mortar [7,8], Mineral-based Composite [9,10], Fiber-Reinforced Inorganic Polymer (FRIP) [11,12], Textile Reinforced Mortars/Concrete (TRM/TRC) [13–19], and cement based dry fiber sheets [20–23]. These methods utilized many advantages of the used cementitious materials. Particularly, the engineered cement-based adhesive provided a much better material compatibility with the concrete substrate compared to the Epoxy-based ones.

Although the above-mentioned strengthening techniques improved the load carrying capacities and met functional requirements of structures under normal service condition, some deficiencies of the used strengthening materials remained. These deficiencies include incompatibility of deformation between the FRP reinforcement and the cement-based matrix, need for larger amounts of FRP reinforcement leading to increasing cost, poor penetration ability of the FRP sheet/plate, and low tensile strength and durability [24,25]. Therefore, a promising strengthening composite system, namely Basalt FRP (BFRP) grid – Ultra-High Toughness Cementitious Composite (UHTCC) for RC structures was explored [26–29]. This new strengthening composite system is expected to provide a dual enhancing effect to the original RC structures due to the high strength of the BFRP grid and the strain-hardening behavior of the UHTCC. Meanwhile, the UHTCC as a bonding agent is expected to suppress the width of cracks and prevent the crack-induced debonding failure due to the multiple cracking behavior of the UHTCC [30–32].

---

[*] Corresponding authors at: Department of Bridge Engineering, School of Transportation, Southeast University, China (W.W. Wang), Pacific Earthquake Engineering Research (PEER) Center, University of California, Berkeley, CA, USA (K.M. Mosalam).

E-mail addresses: universe2009@126.com, 230139502@seu.edu.cn (Y.-Z. Zheng), wangwenwei@seu.edu.cn (W.-W. Wang), mosalam@berkeley.edu (K.M. Mosalam), world789-001@163.com, 230149516@seu.edu.cn (Z.-F. Zhu).

http://dx.doi.org/10.1016/j.compstruct.2017.09.073
Received 25 July 2017; Received in revised form 19 September 2017; Accepted 26 September 2017

Basic research should be conducted before the application of the BFRP grid–UHTCC strengthening system. This paper summarizes such basic research to develop the stress–strain relationship of the BFRP–UHTCC as a Composite Reinforcement Layer (CRL) to be used for future analytical simulation using finite element analysis to predict the flexural and shear load capacities of strengthened RC structures. In the presented study, an experimental program was conducted to investigate the mechanical behavior of the CRL under a uniaxial tensile load. Thirty UHTCC specimens internally strengthened with BFRP grid and a similar six reference specimens without strengthening were tested. The reinforcement ratio of the BFRP grid (0.17%, 0.68%, and 1.16%) and the mix proportion of the UHTCC were the two main test parameters. Moreover, a tensile stress–strain relationship and strength models of the CRL are proposed and validated with the test results to predict the mechanical behavior.

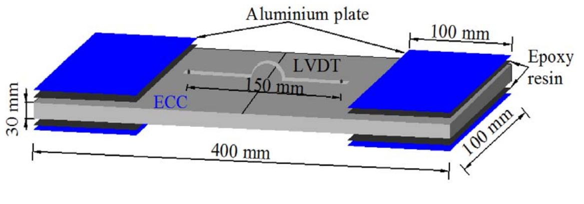
2. Experimental program

2.1. Specimen description

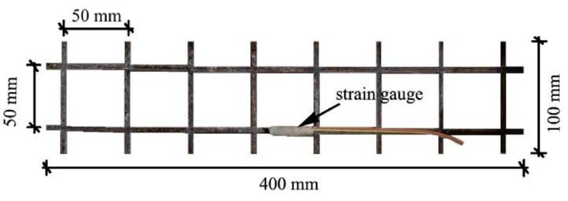
Thirty BFRP grid strengthening UHTCC (BFRP–UHTCC) specimens and six UHTCC specimens without strengthening were tested under a uniaxial tensile load to investigate the mechanical behavior. All test specimens had identical dimensions of 400 mm in length, 100 mm in width and 30 mm in depth, as shown in Fig. 1(a). Four thin square aluminium plates with dimensions of 100 mm × 100 mm × 2 mm were bonded with Epoxy resin to the two opposite sides of the UHTCC substrate at the end regions to make sure the test specimen could be tightly clamped by the tensile test machine, as shown in Fig. 1(a).

In the test program, the non-metallic BFRP grid with the geometric dimensions of 100 mm in width and 400 mm in length was internally embedded in the UHTCC layer. The BFRP grid used in this study was produced by Jiangsu Green Materials Vally New Material T & D Co., Ltd, China. The continuous basalt-based untwisted yarns were used as the reinforcement fibers, which were impregnated with Epoxy resins to form the elements arranged at 50 mm center to center along of the longitudinal and transverse directions of the BFRP grid, as shown in Fig. 1(b).

All test specimens were divided into six groups where each group had six identical specimens as listed in Table 1. Group U0 without strengthening was set as the reference group. The investigated variables in this program were the reinforcement ratio of the BFRP grid and the mix proportion of the UHTCC. Three different thickness of the BFRP grid were used to internally strengthen the UHTCC over-layer: 1 mm for group FU1, 3 mm for groups FU2, FU4, and FU5, and 5 mm for group FU3. In addition, three different mix proportion of the UHTCC were considered to investigate their effect on the tensile force capacity of the strengthened UHTCC specimens: M1 for groups FU1, FU2, and FU3, M2 for group FU2, and M3 for group FU5.



(a) BFRP–UHTCC specimen



(b) BFRP grid

Fig. 1. Dimensions of the BFRP–UHTCC specimen and the BFRP grid. (a) BFRP-UHTCC specimen; (b) BFRP grid.

2.2. Test materials

The material tests of the UHTCC and BFRP grid were conducted to investigate the basic mechanical properties. For the UHTCC, Ordinary Portland cement (P.O 42.5 grade), fly ash (I grade), and silica fume with average diameter between 0.1 μm and 0.3 μm were used. Silica sand with gain size below 0.32 mm was selected as the fine aggregate and a modified polycarboxylic acid-based admixture was utilized as a water reducing agent. Chopped PolyVinyl Alcohol (PVA) fibers with length of 12 mm were used in the UHTCC mix. These fibers are produced by Kuraray Co., Ltd, Japan. The summary of the UHTCC mix designs are listed in Table 2.

The UHTCC material was placed into a steel mold to form the test specimen with dimensions of 400 mm in length, 200 mm in width and 30 mm in depth. During the casting process of the UHTCC, four cube samples with length dimension of 70.7 mm were cast to determine the UHTCC compressive strength for each mix proportion. After curing at a constant temperature of 20 ± 2 °C and relative humidity of 95% for 28 days, all cube samples were tested by a uniaxial compression test machine to determine the compressive strength. The 28-day average compressive strength of the UHTCC for each mix proportion are listed in Table 2.

Nine BFRP grid samples (three samples for each reinforcement ratio of BFRP grid) were tested to investigate the tensile behavior. All tested BFRP grid samples had the same geometrical dimensions as used in the BFRP–UHTCC specimens, as shown in Fig. 1(b). All BFRP grids exhibited a linear behavior until the partial rupture of the fiber reinforcement, as shown in Fig. 2. The average tensile strength of the 1 mm, 3 mm, and 5 mm thick BFRP grids were 357 MPa, 386 MPa, and 416 MPa, respectively. On the other hand, the average elastic modulus of these grids was 51 GPa, 53 GPa, and 57 GPa, respectively.

2.3. Test setup and instruments

After conditioned in a curing chamber with a constant temperature of 20 ± 2 °C and relative humidity of 95% for 28 days, all specimens were tested by a displacement-controlled uniaxial tensile test machine. One end of the tested specimen was firstly placed into the workspace of the steel collets in the universal testing machine, then another one was automatically clamped by the remaining two steel collets, as shown in Fig. 3. The rate of application of the uniaxial displacement was 0.5 mm/min during the whole test. One 'Ω' shape Linear Variable Displacement Transducer (LVDT) was bonded to one side surface of the test specimen to measure the axial deformation. The gauge length of the LVDT was 150 mm, as shown in Fig. 3. Moreover, one electrical resistance strain gauge with a length of 10 mm was attached to the surface of the BFRP grid at the middle section of the specimen to monitor the strain variation, as shown in Fig. 3. The external applied load, the axial deformation of the test specimen and the strain of the BFRP grid embedded in the UHTCC layer were all collected by an automatic data acquisition system.

3. Test results

3.1. Failure modes

Two failure modes of the strengthened specimens were observed in this test program. One mode was the typical fracture failure of UHTCC for the reference UHTCC specimens (i.e. Group U0) due to the internal chopped PVA fibers fractured or slip off from the cement substrate at