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Experimental study on dynamic behavior of GFRP-to-concrete interface

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ABSTRACT

Glass fiber reinforced polymer (GFRP) sheets/plates are widely used to strengthen deficient reinforced concrete (RC) structures. Existing studies show that the effectiveness of externally bonded FRP materials generally depends on the bond between the FRP element and concrete. Most of the researches developed so far have focused on the bond behavior of FRP sheet-concrete interface under static loading. In this work, the bond behavior was experimentally investigated from the dynamic standpoint, through the drop-mass impact test method, with the aim of highlighting the effect of the loading rate on the bond strength. The test results showed that the strain distribution gradient of GFRP sheets under impact loading was larger than under static loading, and that the loading rate significantly influences the bond strength, while only moderately affecting the effective bond length. A practical bond–slip model is here proposed to simulate the GFRP-to-concrete interface bond behavior under dynamic conditions, which considers the strain-rate effect based on the recommendations given in CEB for the strength of concrete under impact loading. Furthermore, starting from the equations given in some existing guidelines, a design proposal is developed to accurately predict the effective bond length and the bond strength of GFRP-to-concrete interface under impact loading.

1. Introduction

Over the past few decades, the adoption of adhesively-bonded composites to strengthen existing concrete structures has steadily increased [1]. Extensive research has been conducted on FRP strengthening of concrete structures, and the effectiveness of the technology largely depends on the bond strength between the FRP sheet and the concrete substrate [1,2]. Bond behavior between FRP reinforcement and concrete has been widely studied and some studies have been adopted by the design guidelines for concrete structures strengthened with externally applied FRP [3–6]. Particularly, some empirical equations have been proposed for bond strength, effective bond length, and bond–slip models.

Extensive experimental research on bond behavior between FRP laminates and concrete has been carried out using single shear tests [7–10], double shear tests [11–14] and modified beam tests [15,16]. Single and double shear tests have been the popular test methods due to their simplicity in design and easy manipulation. Based on experimental tests, some parameters influencing the bond behavior of FRP-to-concrete joints have been investigated. Furthermore, various models have been proposed to predict the bond behaviors of FRP-to-concrete joints [8,10,17–23] based on experimental results, simulation results [24] or fracture mechanics theory.

Civil engineering structures are possibly subjected to dynamic loading, such as blast, impact, and earthquake, during their service life. Some experimental and numerical studies demonstrated that the ductility and blast resistance of FRP-reinforced concrete structures can be upgraded by using externally reinforced FRP [25–29]. However, the limited experimental results were only qualitative in character and could not decipher the impact mechanism of FRP strengthened structures under blast loading [25], and the blast mitigation effectiveness and the percentage improvement of the externally bonded FRP material were not confirmed [26]. A refined numerical analysis with high-strain rate dependent material model and debonding failure model was conducted by Nam et al. [28] for evaluating the FRP retrofitting effectiveness. The debonding failure model under blast pressure was presented based on the FRP to concrete bond model [30], which was developed based on the ideally linear local bond slip relationship and the assumption that the dynamic bond strength is the same as the static bond strength. The test results in Shi et al. [31] showed that the bond behavior of FRP to concrete interface is sensitive to the strain rate, and the interfacial fracture energy, maximum FRP strain and maximum

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shear stress increased with the strain rate as logarithmic functions. Unfortunately, the strain rate measured in the tests of Shi et al. [31] was less than 0.1/s.

There is a lack of knowledge on how the impact load affects bond between FRP and concrete. This paper aims to fill this knowledge gap. To achieve this, a series of 3-point bending tests were carried out at different loading rates to investigate the influence of impact load on the bond behavior of GFRP sheet-concrete interface. The paper presents the summary of the impact tests and some discussions on the test results. Dynamic test results are compared with those of specimens subjected to static bending load to highlight the influence of different loading rates. The measured bond stress–slip curves obtained from impact tests at the GFRP sheet-concrete interface were modeled with a bi-linear law. The proposed model can reasonably predict the effective bond length and the ultimate load for the GFRP sheet-concrete interface under impact loading.

2. Experimental program

2.1. Materials

A concrete with 30 MPa compression strength was used in this study. Coarse aggregate was carbonate-based gravel with the size of 5–20 mm and fine aggregate is common silica-based river sand. Portland cement was used and the mix proportion of concrete is: cement: water: fine aggregate: coarse aggregate = 1: 0.6: 2.2: 3.58. The average cube strengths (f_{cu}), cylinder strengths (f_c) and modulus of elasticity (E_c) at 28 days are approximately 35.1, 28 and 30,900 MPa, respectively. The average measured values of f_{cu} and f_c at the time of the impact tests are 37.3 and 29 MPa, respectively.

As for GFRP sheets, a commercial product (HITEX-G430E) was used, which is a unidirectional tow glass fiber sheet with a nominal thickness of 0.169 mm. The tensile tests were carried out according to ASTM D3039 [32] to measure the mechanical properties of the GFRP fibers. The measured static properties of the tensile strength, modulus of elasticity and ultimate strain were 1434 MPa, 78 GPa and 1.85% respectively.

Ambient temperature curing ESA-TD epoxy adhesive and ESA-TJ epoxy primer were used in the tests. The measured static tensile strength, shear strength, tensile strength normal to concrete, modulus of elasticity and ultimate tensile strain of epoxy adhesive were 65 MPa, 20 MPa, 3.6 MPa, 3200 MPa and 2.0%, respectively. The measured shear strength and tensile strength normal to concrete of the primer were 20 MPa and 3.5 MPa, respectively.

2.2. Specimen preparation

The FRP-to-concrete bond behavior can be determined experimentally by different test setups: double-shear tests, single-shear tests, beam (or bending) tests and modified beam tests [33,34]. Shear tests are not easy to conduct under impact loading, whilst bending tests offer clear advantages in terms of test set-up. Bending tests must be carried out carefully, because the presence of curvature and cracks in the concrete can affect the bond behavior [35–37]. These effects can be minimized by making the concrete blocks stiffer and strong enough to avoid concrete cracking, as observed by Narayanamurthy et al. [38] and by Chen et al. [34], who conducted experimental tests on FRP-to-concrete bond behavior under impact loading. A further advantage of three-point bending tests is that beams can be loaded to failure to simulate the mechanical behavior of FRP sheet-concrete interface under shear (i.e., due to stresses parallel to the interface) and peeling (i.e., due to stresses orthogonal to the interface) stresses [39]. Therefore, bending tests were adopted to experimentally study the GFRP-to-concrete bond behavior under impact loading.

Fig. 1 shows the details of the reinforced concrete beam specimens and the strain gauges layout. The beam specimens consisted of two concrete prisms, with size shown in Fig. 1, connected together by two steel reinforcing bars in the compression zone and a GFRP strip externally bonded to the lower side of the prisms. The two steel reinforcing bars were placed to facilitate manufacturing and installation of the test specimens. The steel bars were designed not to experience any plastic deformation when lifting and installing the specimen and especially during the tests. Shear stirrups were also used to avoid shear failure of the concrete block. The gap between the two concrete blocks was set to 10 mm. One or two layers of GFRP with 510 mm length and 50 mm or 80 mm width were glued to the beam bottom. The right side was made fully bonded by gluing an additional 100 mm wide and 200 mm long GFRP sheet to prevent any slip. On the left side, the bonded and unbonded lengths were set to be 200 mm and 50 mm, respectively.

The surface of the concrete specimens was prepared for bonding by sand grinding to expose the aggregate and smoothen the concrete surface. The surface of the concrete was cleaned by water to remove any dust and loose debris. After air drying, any deposit of grease and oil was cleaned away with acetone. The GFRP sheets were then cut to the sizes shown in Table 1 and bonded to the concrete surface using the bonding adhesive. The epoxy was mixed and then applied using a trowel and impregnating roller.

Twenty-eight externally bonded GFRP sheet reinforced specimens were tested according to the bending test setup. Nineteen identical specimens were tested under impact loading. The investigation was conducted by changing the following parameters:

- the impact velocity v, by changing the drop height (h = 200, 400 and 600 mm) of the drop hammer;
- the bond width of GFRP sheet (b_f = 50 and 80 mm);
- the number of layers of GFRP sheet, n.

Additionally, nine beam specimens were also tested under static loading for obtaining the comparison data on the static bond behavior of GFRP-to-concrete interface. The details of the concrete beam specimens are given in Table 1.

In the current experimental program, the specimens were experimentally prepared and tested at different rates of impact velocity ranging from 1.40 to 2.74 m/s to discover the loading rate effect on bond strength, effective bond length, strain distribution along the bond length and failure mechanisms. The experimental tests in this study were classified into three groups: G50-1 and G50-2 series specimens with 50 mm wide one-ply and two-ply GFRP sheets, and G80-2 series specimens with 80 mm wide two-ply GFRP sheets.

2.3. Test setup and instrumentation

The static tests were carried out on beams in three-point-bending, up to failure to study the mechanical behavior to ultimate of FRP-to-concrete interface [39]. The specimens were simply supported at the two ends with a span of 990 mm. A rubber blanket with size 150 × 120 × 40 mm was simply placed onto the upper surface of the beam at mid-span to distribute the concentrated load (Fig. 1). Loading was applied with a manual hydraulic jack at a rate of about 2 kN/min.

The impact tests were carried out using the drop hammer with up to 1000 kg mass and a maximum drop height of 16 m. This type of setup allows to explore, based on the specimens used, a range of strain rates varying between 0 s^{-1} and 10 s^{-1}. Fig. 2 shows the impact test arrangement with a test specimen in position. The