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Mechanical and Thermochemical Studies Using the Experimental Fracture Mechanics Single Contoured-Cantilever Beam Specimen

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Abstract

Construction practices involving the rehabilitating, retrofitting, and reinforcing of concrete structures using fiber reinforced polymer (FRP) fabrics have been well documented. Experimental efforts to characterize the effectiveness of this technology, however, have included many large scale FRP-concrete tests for strength/stiffness evaluations which do not detect delamination effects; small-scale tests, on the other hand, only provide average interface strength properties that neither describe failure mechanisms nor provide fracture toughness data. In this paper, the experimental fracture mechanics specimen known as the single contoured-cantilever beam (SCCB) was used to obtain important quantitative results of FRP-concrete interfaces as subject to a host of conditions: dry, freezing-thawing, wetting-drying, fatigue, and surface roughness effects on the integrity of the interface bond. The findings of this research effort demonstrate both the importance of surface preparation towards achieving an optimal bond as well as offering a means of gaging rates of degradation of the interface under a variety of commonly encountered construction environments.

Keywords: Fracture mechanics; Single contoured-cantilever beam; Wetting-drying; Freezing-thawing; Fatigue; Experimental investigation

Introduction

External reinforcement by FRP sheets has been used to enhance construction of a variety of structures, e.g. bridges and buildings, as well as different engineering materials, e.g. concrete and steel. A central issue with this technology is in the integrity of the interface bond between the composite fabric and the underlying substrate. In order to quantify and characterize the interface, the experimental fracture mechanics specimen known as the single contoured-cantilever beam (SCCB) was used (Figure 1) to study the bond under dry (Figure 2), i.e., control, conditions, as well as specimens as subjected to commonly encountered environmental field conditions of freezing-thawing (Figure 3) and wetting-drying (Figure 4). Additionally, as bridges are routinely subjected to vehicular traffic resulting in repetitive loading and unloading of the structure, the SCCB setup was used to consider the effects of cyclic fatigue of the interface bond (Figure 5). Finally, the effects of surface roughness on the interface bond was also considered through three categories of concrete surface preparation: straight out of the mold, belt-sanded, and sand-blasted (as seen from left to right in Figure 6) [1].

This work summarizes the experimental fracture results of the SCCB specimens under the aforementioned five categories of conditions. As expected, very clear losses to the integrity of the interface bond resulted, on the one hand, for specimens placed in the harsh thermochemical environments described in the following, and the sheer importance of proper surface preparation was discovered for specimens subjected to repetitive mechanical stresses of cyclic fatigue, on the other hand.

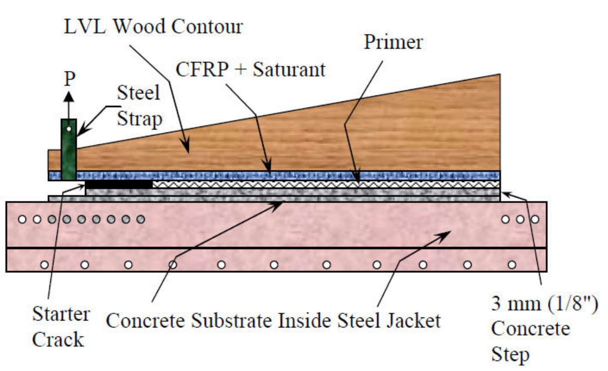

Figure 1: SCCB specimen.

Dry Fracture

Fracture testing (Figures 1 and 2) was conducted on two types of dry specimens distinguished herein as pristine-dry and companion-dry, both of which were used for the specific purpose of gathering benchmark control data. The pristine-dry specimens were fractured at the 28-day maturation period of concrete, whereas the companion-dry specimens were set aside and fractured at the target dates corresponding to their aged counterparts. On average the pristine-dry fracture results were found to have a value of 617 J/m^2 whereas the companion-dry specimens had the following average values: for the wetting-drying companion-dry specimens corresponding to 20 and 30 cycles, the fracture results were 744 and 782 J/m^2, respectively; likewise, for the freezing-thawing companion-dry specimens at 50, 100, 150, 200, and 300 cycles, the fracture results were 602, 622, 729, 785, and 811 J/m^2, respectively. The increase in fracture values over time follows reason as both the epoxy at the interface, and more significantly, the underlying concrete substrate, make gains with age [2].

Figure 2: Dry fracture of interface bond.

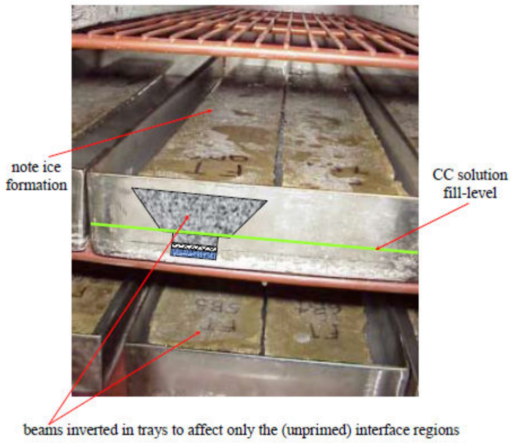

Figure 3: Freezing-thawing.

Figure 4: Wetting-drying.

Effects of Freezing-Thawing

A single freezing-thawing cycle was designed to take the FRP-concrete interface as subjected to a calcium chloride environment (Figure 3) from room temperature (20°C) down to -20°C in a two hour time frame, sustain that freezing-level for two hours, then ramp back up to room temperature in two hours. The percentage reduction in fracture values of specimens at 50, 100, 150, 200, and 300 cycles was as follows: 94, 86, 82, 71, and 61%, respectively [3].

Effects of Wetting-Drying

Two separate environments of wetting were used in this study: one, in a bath of 10% sodium sulfate at a pH range of 6.2-6.5, and another in a bath of sodium hydroxide at a pH of 12 (Figure 4). A single wetting-drying cycle constituted 3 days of wetting and 4 days of drying in an environmental chamber maintained at 40°C and 50% relative humidity. The percentage reduction in fracture values of specimens at 10, 20, and 30 cycles was as follows: 86, 83, and 68%, respectively, for the sodium sulfate specimens, and 90, 71, and 59%, respectively, for the sodium hydroxide specimens [1].

Effects of Cyclic Fatigue

Cyclic fatigue tests (Figure 5) were performed on FRP-concrete specimens in which the following two parameters were considered: load ratios (R), i.e., the ratio between the minimum and maximum load, of R = 0.25 and R = 0.50; also frequencies (f) of: f = 3 Hz and f = 5 Hz. Crack propagation rates (da/dN) were found to range between $da/dN \approx 4 \times 10^{-6}$ in/cycle to $da/dN \approx 200 \times 10^{-6}$ in/cycle, depending in particular to the degree of surface preparation of the underlying concrete substrates, as explained in greater detail in the following subsection. Interestingly, it was found that sand-blasting the surface resulted in longevity of the interface bond exceeding 20 million cycles for the dry specimens, indicating imperviousness due to the phenomenon of cyclic fatigue at such R and f values [4-5].

Surface Preparation

The fracture toughness of the interface bond was also considered under three different levels of surface roughness of the underlying concrete substrates: straight out of the mold, a moderately roughened surface as achieved by belt-sanding (at 50-grit), and a highly roughened surface as achieved by sand-blasting (with fine #20 mesh-sized grains). By using a Surfanalyzer 5000 instrument with an accuracy down to 125 nm, three broad categories of characterization were consequently defined: low (< 10 µm), medium (10 µm – 50 µm), and high (>50 µm) as seen from left to right in Figure 6. Belt-sanding was found to improve the fracture toughness of the interface bond in a range of 20–50% over the mold surfaces, whereas sand-blasting yielded fracture values that were nearly three times higher in comparison to the smooth, straight out of mold, samples [4,5].

Figure 5: Cyclic fatigue.

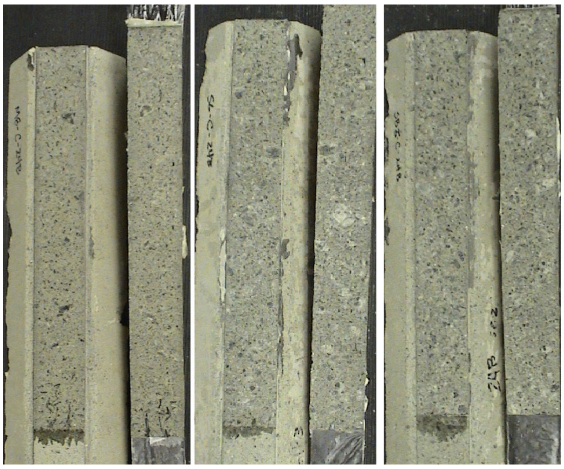

Figure 6: Surface preparation.

Concluding Remarks

The results and findings of this comprehensive experimental study demonstrate that the integrity of the interface bond was compromised by as much as: (i) 61% for 300 cycles of freezing-thawing under a calcium chloride environment, and (ii) 68% and 59% for 30 cycles of wetting-drying specimens under sodium-sulfate and -hydroxide environments, respectively. Crack propagation rates having a range of $da/dN \approx 4 \times 10^{-6}$ in/cycle to $\approx 200 \times 10^{-6}$ in/cycle were found by which service life estimates of the interface bond can be determined through integration; specimens with adequately prepared concrete surfaces demonstrated an imperviousness to the phenomenon of cyclic fatigue. The sheer importance of this point of surface roughness to the integrity of the interface bond was demonstrated for specimens having been prepared by sand-blasting, resulting in near threefold gains in values of fracture toughness.

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