Structural health monitoring of structures repaired with FRP

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Abstract

Sprayed FRP is a novel method developed at the University of British Columbia which has been very successful in repairing damaged structures is Sprayed FRP. The key to a successful and optimal usage of FRP in strengthening and rehabilitation is in our ability to understand and effectively engineer Substrate-FRP bond. In this paper, performance of FRP as a repair material is studied by structural monitoring of the substrate and the FRP sprayed patch.

In this study, 35x10x10 cm concrete beams are sprayed with FRP and tested under four- point loading. The substrate and repair material response to loading is monitored using strain gauges carefully installed at different locations of the structure. Ten 10-mm one-directional and two bi-directional strain gauges are used. Data is obtained using data acquisition machine and converter software. The load-stain curves for the strain gauges are graphed. The measurements at the gauges located at the same level are compared and strain divergence is discussed.

Possible approaches are discussed to model the gradual process of bond interface. This is the basis for a comprehensive damage model capable of predicting the performance of repaired structures under various static and earthquake loading. A field performance of these repairs will also be discussed. The case study is a bridge in Victoria, British Columbia, which was repaired by sprayed FRP and has been monitored over the past three years by the materials group of UBC under Dr. Banthia's leadership.
Keywords: fibre reinforced polymer, concrete, structural health monitoring, bond, sprayed FRP.

1 Introduction

Infrastructure deterioration has been a global crisis in the recent decade. In the United States alone there are more than 200,000 deficient bridges, and there are approximately 30,000 in Canada. 150 to 200 spans fail each year, sometimes with tragic consequences. The cost of strengthening or repairing the 30,000 deficient bridges in Canada is about $44 billion. It will take $5 billion to rehabilitate the 5,000 parking garages that are in a state of utter disrepair.

The most common method for repair/strengthening has been to externally bond steel plates to the structure, but lately, fiber reinforced polymers (FRPs) are slowly replacing steel in these applications owing to their superior properties such as a high strength to weight ratio and excellent resistance to corrosion. Fiber reinforced polymers (FRPs) consist of high-strength fibers (carbon, glass, or aramid) embedded in a polymeric matrix (epoxy, vinylester, etc). They have been largely used in new construction and repair and rehabilitation of existing structures. Figure 1 shows an application of FRP in repairing Sins Bridge, Switzerland. FRP can be used as a confining material in columns to increase the load bearing capacity. It is also utilized in flexural and shear strengthening. Repairs with FRP could restore or even increase the ultimate failure capacity or could just simply be used for aesthetic purposes. Figure 2 shows the concept of shear and flexural strengthening by fiber reinforced polymer.

Figure 1: FRP repair in Sins Bridge, Switzerland [1].

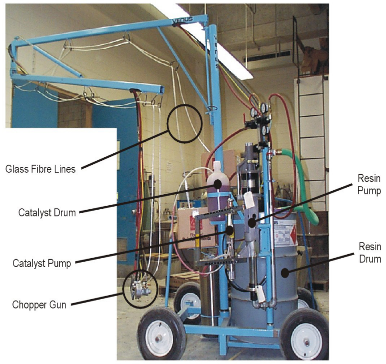
Figure 2: Left: CFRP (Sika Carbodur) flexural reinforcement, Right: CFRP (Sika Carbodur) shear reinforcement [1].

The key to a successful and optimal usage of FRP in strengthening and rehabilitation, however, is in our ability to understand and effectively engineer concrete-FRP bond. Unfortunately, our understanding of the basic mechanisms that allow FRP to bond to concrete, the processes that promote degradation of the bond, and many other variables that control and define bond is extremely limited.

2 Sprayed FRP technology

The FRP Spray technique was developed at the University of British Columbia in conjunction with ISIS Canada by Dr. Nemkumar Banthia. The technique consists of spraying polymer and short, randomly distributed fibers on the surface of concrete such that a 2-diemnsional random distribution of fibers is achieved on the surface. Three basic intergradient of the final composite are handled simultaneously by the pumping and spraying equipment. The resin and catalyst are fed separately into a spray gun and then spayed after mixing. The glass fiber in a revolving format is fed into a chopper unit mounted on top of the spray gun. These two streams combine and continue onto the spraying surface together. After spraying, a roller is used to force out any entrapped air voids and make a consistent thickness [1]. Figure 3 shows the spray gun and spraying process.

Lab-tested against existing repair techniques, the FRP Spray has proven to be the strongest and least costly method of bridge deck repair. The technique is estimated to cost about half the amount of traditional steel-jacketing repair techniques, and a third less than fiber reinforced polymer jacketing. Unlike steel jacketing that corrodes over time, FRP spray does not corrode, adding to long-term cost savings. The versatile repair technique can also be used to re-fit other construction surfaces such as steel and timber, and has applications for seismic upgrading in a variety of structures.



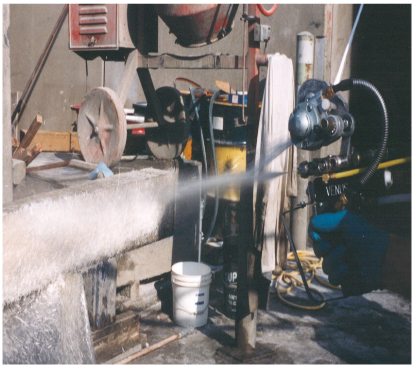


Figure 3: Left: UBC portable spray gun, Right: Spraying Process [1].

3 Structural health monitoring

3.1 Specimens

Notched 30x10x10 cm beam specimens were used. Different sets of beam with Notch lengths of 4 and 6 cm were tested. Two methods of repair: FRP Spraying and FRP wrapping were used. The challenge at the beginning was the low shear strength of concrete compared to the FRP-Concrete shear bond which leads to the shear failure of the beam instead of de-bonding. This issue was overcome by using FRC concrete (with higher shear capacity) and also using 30x10x3.3 cm specimens (Figure 4).

3.2 Test set up

One side FRP sprayed beam specimens (30x10x10 cm) under 4-point loading are utilized in this project. Ten 10-mm one-directional strain gauges and two bi-directional are used for each specimen. The specimens are pre-cracked to dictate the initiation and direction of de-bonding. A closed-loop system for stable crack growth was used and the specimens were tested under quasi static and cyclic loading.

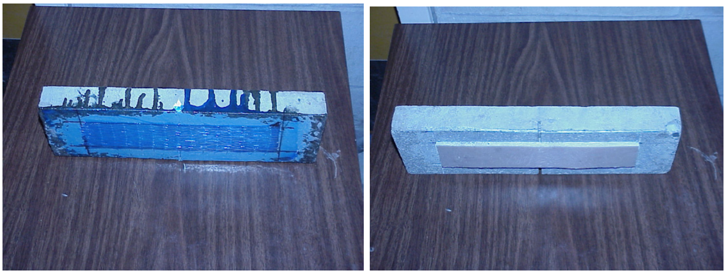


Figure 4: Left: beams with wrapped FRP, right: beams with sprayed FRP.

3.3 Results and discussion

The samples were initially tested under quasi-static 4-point bending loading. The results are shown in Figure 5. The nonlinearity of the curve is an indication of the bonding forces in action from the first steps of loading. The failure in this case was very sudden which avoided a proper evaluation of post-de-bonding behavior.

In the next phase, the system was heavily instrumented and tested under cyclic loading. The substrate and repair material response to loading is monitored using strain gauges carefully installed at different locations of the structure. Data is obtained using data acquisition machine and converter software. The load-stain curves for the strain gauges are graphed. Test set up is shown in figure 6.

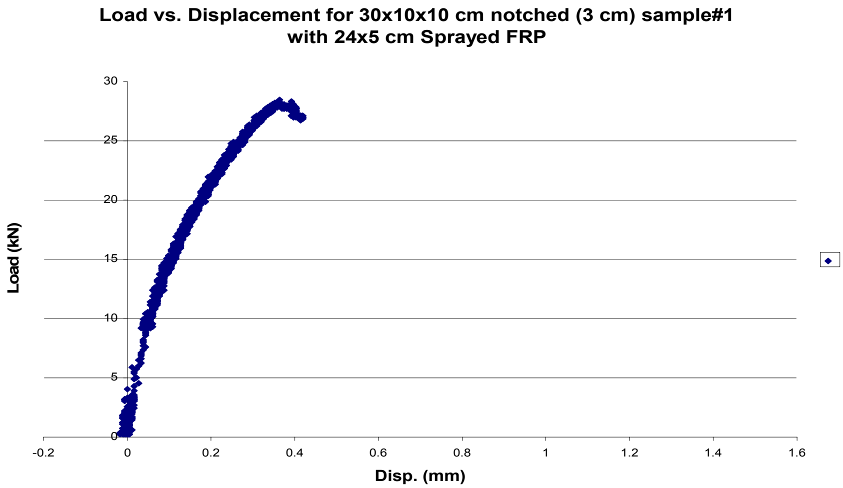


Figure 5: Load vs. Displacement for 35x10x10 cm notched (3 cm) with 24x5 cm sprayed FRP.

Figure 6: Left: Instrumentation with uni-directional and bi-directional gauges; right: FRP-concrete bond monitoring test set-up.

A gradual divergence between the strain obtained from gauges on FRP and concrete was measured, which is used to define a de-bonding criteria (Figures 7 and 8). The inter-laminar strain measured from bi-directional gauges indicates a potential source of delamination stresses, which help the de-bonding phenomenon.

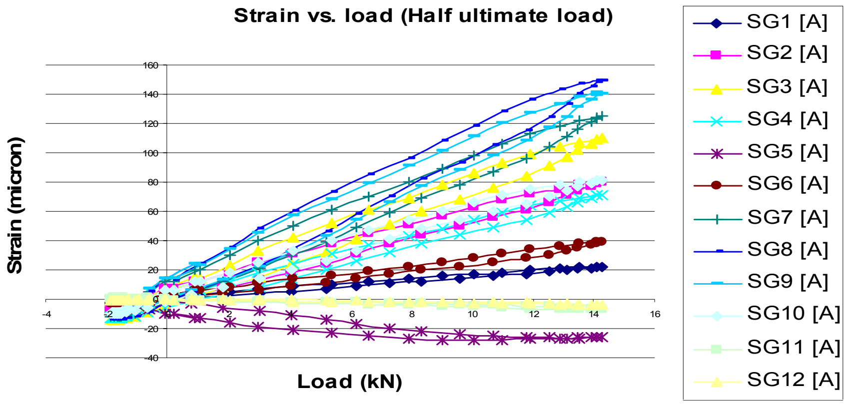


Figure 7: Strain vs. load in different strain gauges on FRP and Concrete.

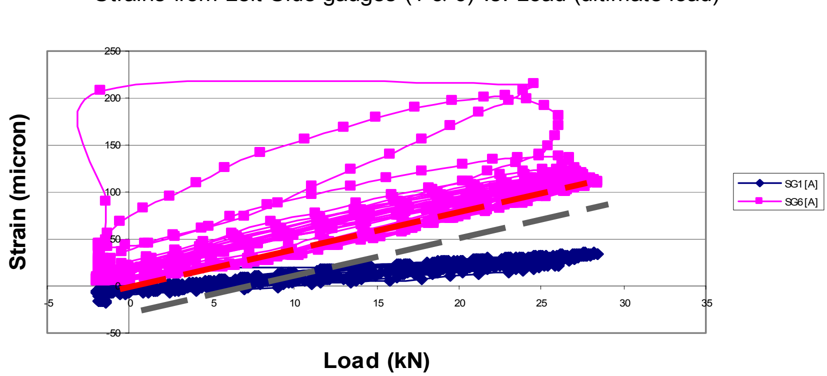


Figure 8: De-bonding progress, definition of de-bonding criteria.

4 Case study

The technique of sprayed composites was applied to the Safe Bridge on the Vancouver Island (near Duncan, British Columbia) that needed shear strengthening. Of the three channel beams salvaged from the old bridge, one was rehabilitated with the sprayed GFRP technique while a second was retrofitted using a commercially available continuous fiber wrap system, also composed of E-glass .

Before the application of GFRP Spray to the Safe Bridge, the bridge was fully instrumented. Strain gauges were placed on all eleven girders at mid-span and these were then sealed for long term monitoring. The bridge was then tested and calibrated for its response prior to placement of GFRP Spray retrofit by loading it at various locations using a fully loaded 28-ton dump truck. After the application of the spray, the bridge was load tested again by loading it at various locations using a 28-ton dump truck (Figures 26a and 26b). The benefits of the spray were observed (Figures 9 and 10).

Figure 9: Instrumentation is Safe bridge, Victoria, BC: Left: Traditional Sensors, right: fiber optics [1].

Figure 10: Repair and testing set-up in Safe Bridge, Victoria, VC: left: spraying operation, right: loading test [1].

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