Laser Profilometry for Concrete Substrate Characterization Prior to FRP Laminate Application

By Norbert H. Maerz, Antonio Nanni, John J. Myers, and Greg Galecki

Figure 1: Application of FRP sheet on one-way joist

The use of fiber reinforced polymers (FRP) for reinforcement of aging and deteriorating concrete members has emerged as a viable and cost-effective alternative to traditional repair and strengthening techniques. Their use enables upgrading of deficient structures to meet today's design standards (Crasto et al., 1996; Myers et al., 2000). The load-carrying ability of structures such as beams and columns can be enhanced by externally attaching the FRP laminates to the concrete surface. FRP laminates have high tensile strength-to-weight ratios and high stiffness, and can be easily installed by a manual lay-up process. Because fibers and resins are non-corrosive, they are ideally suited for the repair and retrofitting of concrete bridges and parking structures where high concentrations of chlorides from de-icing salts are found.

Externally applied FRP sheets or laminates are impregnated in-situ and bonded directly to a concrete surface with an epoxy (see Figure 1). These FRP materials are often applied to provide additional flexural or shear strength capacity for deficient structures or structures where a change in the occupancy or usage occurs. The overall performance of the system and the parameters that affect delamination (see Figure 2) depend highly upon the quality of the bond between the concrete and the laminate. Experience has shown that when delamination of the FRP sheets occur at the substrate level, the load-bearing capability of the strengthened member is compromised except when FRP laminates are used to confine members in axial compression. Research has indicated that the bond strength between the epoxy adhesive and the concrete depends on a number of factors, including the material properties of the epoxy as well as the properties of the concrete substrate (Miller and Nanni, 1999). The strength of the epoxy is affected by how it is stored, handled, installed, and cured. The epoxy-concrete bond strength is affected by the strength, roughness, and cleanliness of the prepared concrete surface.

Ongoing research at the Center for Infrastructure Engineering Studies at the University of Missouri-Rolla is focusing on ways to reduce the incidence of delamination of FRPs by developing new specifications for FRP installation.

Substrate Preparation

The effectiveness of any externally bonded FRP reinforcement is affected by the quality of the bond between the reinforcement and the concrete surface to which it is applied, as well as by the strength of the concrete substrate. Improper bonding may cause failure resulting from the FRP reinforcement detaching or peeling from the concrete substrate.

Surface preparation is the process by which sound, clean, and suitably roughened surfaces are produced on concrete substrates. These include detergent scrubbing, low-pressure water cleaning, acid etching, grinding, sandblasting, shot blasting, scarifying, needle scaling, scabbing, high-pressure water jetting, flame blasting, and milling (ICRI, 1997) (Figure 3). Each of these methods has its advantages and disadvantages in the terms of effort and efficiency of cleaning, removing unsound material, and roughening the surface.

Role of Substrate Roughness

Assuming a clean, sound, prepared surface, one of the principal factors affecting the bond behavior between the concrete and epoxy is the roughness of the concrete substrate. Too smooth a surface may result in poor bonding. Too rough a surface will require the addition of a putty filler under the epoxy. An optimal level of roughness will result in maximum bond strength while reducing the additional cost and effort of placing putty filler. While this optimal level of roughness has not been characterized to date, preliminary bond characterization work has indicated that this level of roughness impacts the loading level at which de-lamination between the two materials occurs. Based on this initial study, too little or excessive roughness results in less-than-optimal bonding characteristics.

To that end, a portable device has been developed to measure the roughness of concrete surfaces. If surface roughness was measured accurately and controlled during the installation process, more reliable bond strength and bond failure mode could be predicted. This device can be used as a quality control tool to characterize surface roughness and identify when an adequate surface preparation has been attained. The method uses laser striping and image analysis.

Figure 2: Delamination of externally bonded FRP sheets

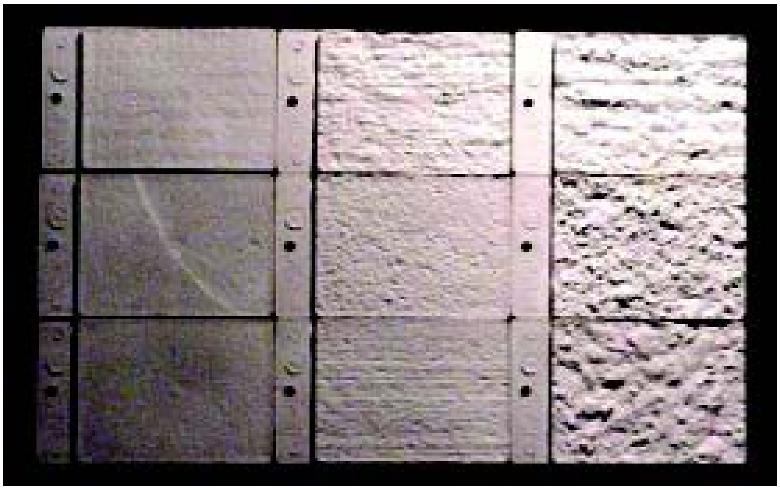

Figure 3: Plastic model concrete surface profiles. The profiles are ordered 1 to 9 in order of increasing roughness, and correspond to acid etching, grinding, light shotblast, light scarification, medium shotblast, medium scarification, heavy abrasive blast, scabbing, and heavy scarification

Characterization of Concrete Surface Roughness

State of the Art

There are currently no means to effectively measure roughness of concrete. The state of the art is to subjectively compare the concrete surface to concrete surface profiles (CSP) in the form of nine plastic model surfaces produced by the International Concrete Repair Institute (ICRI, 1997) (Figure 3).

Principle of Laser Profiling

A new, portable, concrete roughness testing device—an optical laser-based imaging system—has been developed along the principles of Schmaltz microscope (Schmaltz, 1936) and the method of shadow profilometry (Maerz and Franklin, 1990), that uses a laser profiling line rather than a linear beam of light or shadow edge. This procedure is called "laser striping." This new device is a portable imaging device that can be used to measure roughness in both research and production environments.

Imaging Principles

Using laser striping, a rough concrete surface is illuminated with thin slits of red laser light at an angle of 45 degrees, and the surface is observed at

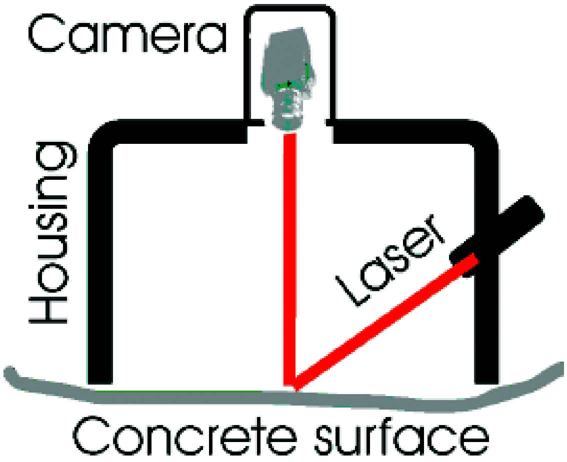

Figure 4: Schematic representation of the laser-profiling equipment

Figure 5: Prototype of the laser profiling device, measuring six manufactured concrete surface profiles

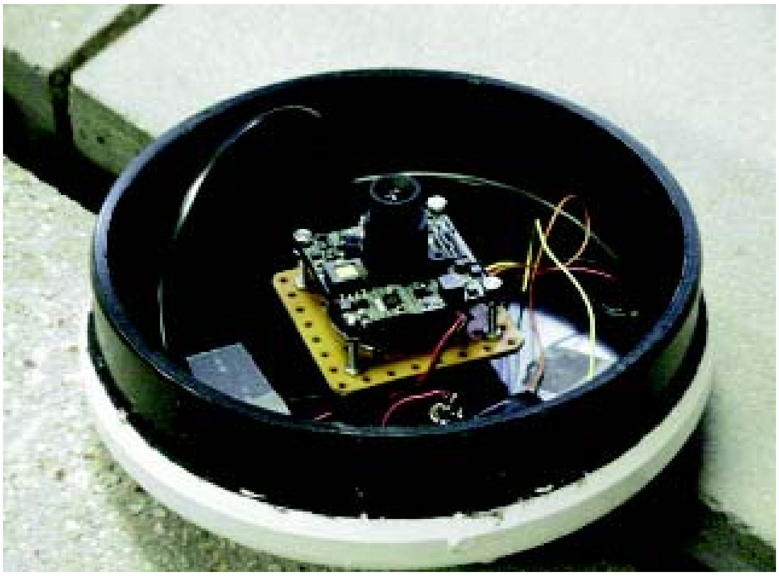

Figure 6: CCD camera

90 degrees (Figures 4-8). The projected slit of light appears as a straight line if the surface is flat, and as a progressively more undulating line as the roughness of the surface increases. A striping laser with 11 stripes is mounted at 45 degrees with a standoff distance of about 170 mm to the surface. Lasers with 1, 5, or 11 stripes were used.

A high-resolution board CCD camera is mounted vertically in the housing with a standoff distance of about 150 mm.

A band pass filter is placed over the camera lens that rejects both high- and low-frequency light and allows only the laser light to pass through to the camera.

The video image of the laser stripes is digitized with a PCMCIA frame grabber on a laptop computer, at a resolution of 640 by 480 picture elements (pixels) (Figure 9).

Image Analysis Principles

Classical image analysis techniques are used to transform the image of the laser stripes (Figure 9) into a series of 11 profiles in x-y space. Each profile is analyzed to provide various statistics. The most useful statistic is the micro-average inclination angle (i_A), which is the average of the pixel to pixel angles of the stripe profile:

$$i_A = \frac{1}{n}\sum_{i=1}^{n}\left|I_j\right|$$

where

n = number of evenly spaced sampling points;

I = inclination angle between points along sampling line.

In effect, the roughness of the surface is characterized by the absolute value of the average inclination angle of surface along a series of linear profiles.

Measurement Examples

Manufactured Concrete Surfaces

For the purpose of evaluating the measurement technique, two sets of concrete surfaces were studied. Two sets each of six concrete blocks (300 mm x 300 mm x 100 mm) were prepared (Figure 5). Five of the concrete surfaces were prepared by sandblasting. Surfaces 1-5 were progressively made rougher by increasing the duration of sandblasting. (While there was nominally a linear increase in the duration of sandblasting, the difference in roughness between samples was found to be decidedly non-linear). Surface 0 was made smooth by grinding.

For the purpose of characterizing the surfaces, measurements were taken for each surface at three

Fig. 7: Line laser

different orientations, two different positions, with two replicates for each measurement. In total, 144 measurements were taken. All measurements were taken with an 11-line laser at a 100 mm base length.

The result of the analysis (Figure 10) reveals that the surfaces can be characterized in terms of the average inclination angle of the profiles. While surfaces 0 and 1, and surfaces 5 and 6 are very distinctive, surfaces 2 and 3 are very similar to each other. This reflects the fact that the actual roughness of the two surfaces is very similar.

The experimental design was set up to measure surface roughness as a function of the different control blocks, set of blocks, the profile orientation, profile position, and using replicates for control.

Analysis of variance indicated that, for these samples, the differences in measured roughness were significant, orientation was not significant (roughness was not an isotropic), and position was significant (roughness was inhomogeneous).

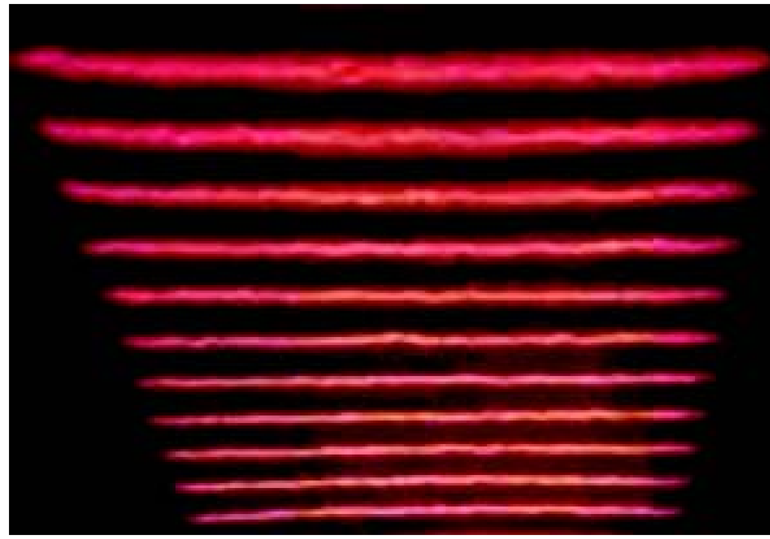

Figure 8: Image of a concrete surface being illuminated by an 11-line generator

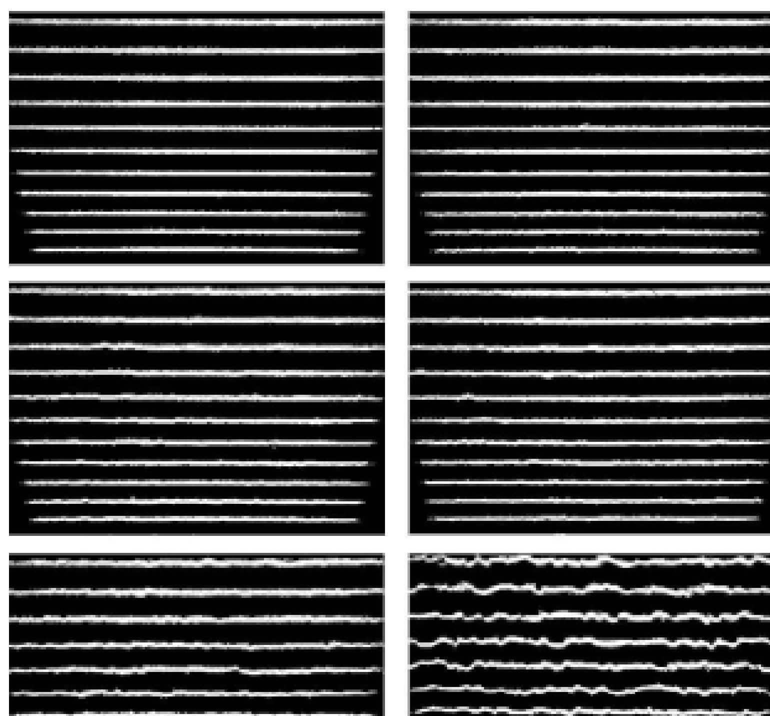

Figure 9: Laser profiles for the 6 different roughened concrete surfaces of Figure 5

Summary

The manufactured roughness is undoubtedly an important requisite in the proper adhesion and performance of fiber reinforced polymers on concrete substrates. Characterization of that roughness is then also of significant importance, although the current state of the art allows only subjective evaluation of roughness, rather than a quantitative measurement.

A prototype of a new device for measuring roughness in the laboratory and in-situ has been developed. Preliminary studies have shown the device to be effective in measuring and characterizing roughness.

Ongoing research has been initiated to develop construction specifications, as warranted, and to determine the level of influence surface roughness

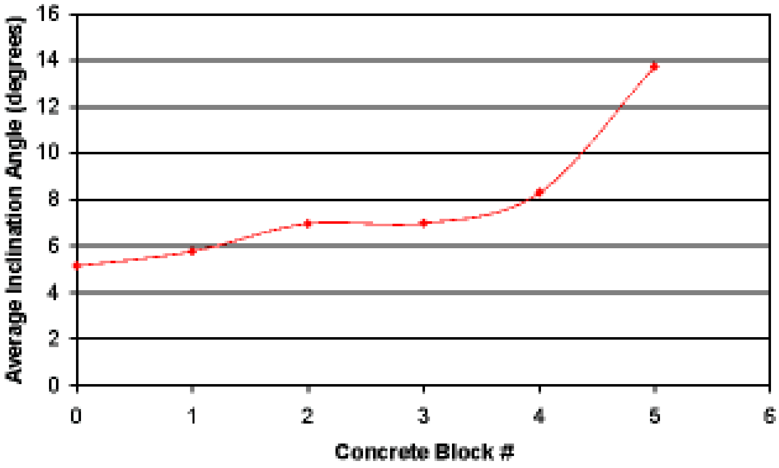

Figure 10: Roughness measurement results for the six concrete surfaces in terms of the average inclination angle of the profiles

has on bond performance. Current studies are looking at surfaces generated by water jets and sandblasting. Ultimately, the roughness measurements will be related to FRP bond strength in an effort to correlate surface roughness to bond strength. In addition, the research program intends to provide specifications of acceptable and optimum levels of roughness, and if appropriate, specifications for a measuring device that can be used in the field as a quality assurance tool.

Acknowledgments

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