A QUANTITATIVE STUDY ON BOND BEHAVIOR BETWEEN FIBER-REINFORCED POLYMER (FRP) AND CONCRETE INTERFACE USING INFRA-RED THERMOGRAPHY (IRT)

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ABSTRACT

Carbon fiber-reinforced polymer (CFRP) has become an important and widely accepted material to rehabilitate deteriorating concrete structures. The quality of the bond between the CFRP and concrete elements is crucial to durability of the rehabilitated concrete structure. However, flaws/voids between CFRP and concrete interfaces can reduce significantly the effective contact area and therefore the overall bond strength at these interfaces. These flaws are not readily noticed by naked eyes, but can be detected non-destructively and effectively by using non-contact Infra-red thermography (IRT). This paper presents a method for the identification of these delaminations using IRT. The IRT results depended on distinct rates of heat transfer induced by sound and flaw areas of FRP. Through a series of experiments, images with temperature distribution over the CFRP surfaces were captured after applying a controlled contact heat source on the CFRP surfaces. These images were frequently (25 frames per second) and continuously (for 30 seconds) acquired so that the transient differences of heat transfer could be closely monitored. The digitized images were analyzed with a number of image processing techniques to quantify the boundaries and areas of flaws found in the FRP/concrete interfaces. Based on testing of 15 specimens and by comparing with the actual physical flaw sizes, the estimation based on this new IRT technique was 85% accurate.

KEYWORDS

Bond behavior, concrete-FRP interfaces, IRT, Quantitative analysis.

INTRODUCTION

Infrared thermographic (IRT) technique, as one of the most promising nondestructive testing techniques, has been widely accepted as an effective means to identify and quantify the unseen surface flaws in a wide range of composite materials. Some of the recent applications of IRT include the detection of defects due to aluminium corrosion (Vallerand and Maldague, 2000), in glass-epoxy laminates (Giorleo and Meola, 2002), in plastic lid (Legrand, et al., 2002) and in CFRP (Starnes, et al., 2002, 2003). In these multi-disciplinary applications, the embedded flaws are not readily noticed by naked eyes, but can be detected non-destructively, remotely and effectively by using non-contact IRT. It is because the presence of a defect (i.e. air voids) in a composite/homogeneous material reduces the heat diffusion rate once a thermal stimulus is applied. The fundamental principles of using IRT to solve a variety of civil engineering and nondestructive testing problems have been well documented by Maldague (1993), Bungey, et al. (2006), and Malhortra and Carino (2006); whilst an excellent review of the recent IRT applications was given by Meola and Carlomagno (2004). During the early application of IRT in civil engineering, most published works concentrated on simply positioning the embedded flaws qualitatively, while it is more necessary to quantify the flaw boundaries and sizes so that the extent of damages and their effects on structural integrity and durability can be assessed. Starnes, et al. (2002, 2003) studied quantitative characterization of flaws embedded in CFRP; but their works emphasized on matching their developed finite element models with limited experimental data support. With a large amount of time-lapsed thermographic experimental data, this paper attempts to define the boundaries and estimate the sizes of flaws embedded within the concrete and the CFRP interfaces.
EXPERIMENTAL SETUP

Materials and Specimens

CFRP strips (sized 60 x 200mm) and concrete beams (sized 150 x 150 x 500 mm) were bonded using primer and resin (Sika 300\textsuperscript{TM}), as shown in Figure 1. The bond between the CFRP strips and the concrete elements were allowed to harden for at least 14 days before the IRT tests were conducted, so that the specimens were dried sufficiently. The nominal thickness of the CFRP strips was 0.165mm, while the primer and resin were mixed with the epoxy and the hardener. The mixing ratio of the epoxy and the hardener by weight was 3:1. The epoxy and the hardener were mixed for at least 5 minutes using an electric mixer before applying to the concrete surface and the CFRP strips. A number of physical properties of the CFRP sheets and Sika 300\textsuperscript{TM} were determined according to the flat coupon tensile tests (ASTM, 1995; Lam and Teng, 2004) and the test results are reported in Table 1.

<table>
<thead>
<tr>
<th>Type of specimen</th>
<th>Number of specimens tested</th>
<th>Elastic modulus (MPa)</th>
<th>Elongation (%)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm wide CFRP sheet</td>
<td>5</td>
<td>254,860</td>
<td>1.482</td>
<td>4,163</td>
</tr>
<tr>
<td>25 mm wide Sika 300 sheet</td>
<td>5</td>
<td>26,354</td>
<td>1.212</td>
<td>86</td>
</tr>
</tbody>
</table>

Table 1. Tensile tests on CFRP flat sheets before exposure

Instrumentation

The infrared thermo-imager used in the experiments was FLIR Prism DS IR which receives infra-red radiation ranging from 3.6 to 5 \( \mu \)m. Since digital interfaces were not available at the time of the test, gray-scale video images in analog format were output to the computer terminal via a video output. These analog video images were then encoded to a sequence of 8-bit digitized and two-dimensional thermograms/pixel arrays through an A/D process. The A/D process was controlled via the ‘National Instrument\textsuperscript{TM}', frame grabber and a software program developed under the LabVIEW\textsuperscript{TM} and IMAQ\textsuperscript{TM} environment. In each experiment, the software program was designed to capture and process the thermograms frequently (sampling rate = 25 frames per second) and continuously (for 30 seconds) so that the transient differences of heat transfer could be closely monitored. For each experiment which lasted for 30 seconds, 750 nos. of frame images were captured.

The 8-bit digitized thermograms contain pixel values ranging from 0-255. This range was assumed to represent \textit{linearly} the temperature values ranging from the lower bound to the upper bound. The lower bound refers to 22\(^{\circ}\)C which was approximately the room temperature during the test; while the upper bound refers to 40\(^{\circ}\)C which was approximately the controlled heated temperature. It must be noted that these temperature values were indicative only and not inherently true since (1) the emissivity of the CFRP was not calibrated and (2)
The thermal stimulus used for the experiment was a device that could be heated to constant surface temperature (40°C). It was applied directly on the CFRP surface to supply and distribute heat energy on the specimens evenly so that the defective and the sound areas within the CFRP/concrete bond can be distinguished and characterized through different diffusion rates.

**Procedures**

For each test run, the specimens were heated up with a warm bag for half a minute and 750 nos. time-lapsed thermograms (in a rate of 25 frames per second) were captured continuously for 30 seconds, as shown in Figure 2. Thermal event changes with time because heat transfers to the ambient environment transiently with time. Selection of a single and an appropriate thermogram from the image sequence is required to extractly define the flaw boundaries. The selection criteria is generally based on the thermogram with greatest thermal contrast (Maldaugue, 1993) which is the temperature differential of the flaws normalized by that over a sound area, according to equation [1].

\[
C(x, y, t) = \frac{\Delta T_{def}(x, y, t)}{\Delta T_{sound}(x, y, t)} = \frac{T_{def}(x, y, t) - T_{def}(t_0)}{T_{sound}(t) - T_{sound}(t_0)} \quad \text{..... (1)}
\]

where

- \(C(x, y, t)\) is the spatial thermal contrast at time \(t\),
- \(T_{def}(x, y, t)\) is the spatial temperature (represented by pixel values) at which the defects are found at time \(t\),
- \(T_{def}(t_0)\) is the spatial temperature (represented by pixel values) at which the defects are found initially,
- \(T_{sound}(t)\) is the temperature (represented by pixel values) at a particular position at which no defects are found at time \(t\),
- \(T_{sound}(t_0)\) is the temperature (represented by pixel values) at a particular position at which no defects are found initially, and
- \(T_{def}(t_0) = T_{sound}(t_0)\) if the defective and sound areas in the specimen were assumed to attain the same temperature.

After extraction of the appropriate thermogram with the greatest thermal contrast, the “actual” geometrical shape of the defect was estimated by the “apparent” shape deduced from the pixel profile determined in horizontal and vertical lines (Note: pixel is an indicator of temperature in this context). The latter was found to
be very close to the steepest temperature gradient computed on the sample surfaces over the defects (Krapez and Cielo, 1991; Maldague, 1993). We extracted column (in y-y direction) and row (in x-x direction) pixel slices entailed in the thermogram with the greatest thermal contrast. Each of these columns and rows pixel profiles was segmented about the mid-point (i.e. center of the flaw) to construct two halved pixel-profiles. The data from these halved pixel profiles was then curve-fitted into the respective 4th order polynomials which were found to represent the data properly. The 4th order polynomials were subsequently differentiated twice to obtain another 2nd order equation, where one of the respective roots in this equation is the inflection point exhibited in the fitted 4th order polynomials. The number of pixels from this inflection point to the mid-point in the flaw thermogram was then counted. This count represented the apparent half-width of the flaws at a particular column or row, which was computed after a direct conversion from number of pixels to actual distance (in mm). Summation of the total apparent half-width gave the “apparent” sizes of the flaws in each row/column halved pixel profile. This process was programmed to iterate for each column and row entailed in the flaw thermogram and was programmed to repeat for each area with slow thermal decay (i.e. area of flaw), as shown in Figure 3. A study of 15 nos. laboratory specimens concludes that the method of flaw size estimation described in this paper yields an accuracy of 85%. The actual flaw size was determined by physically opening up the specimens after the test. The result of comparison is reported in Figure 4.

Figure 3. The CFRP strip after open-up (top left), Estimated flaw boundary in the thermogram (bottom) and the 3D plot of the flaw (top right)
CONCLUSION

This paper concludes that the boundaries and the areas of the flaws embedded within a composite (such as CFRP-strengthened concrete) can be estimated quantitatively by making use of a sequence of the time-lapsed thermograms and a developed computational algorithms. This method has the advantages of not requiring calibration of material’s emissivity and not dependent on the knowledge of exact power delivered by the applied thermal stimulus, provided that the thermal contrast between the flaw and sound areas are sufficient. It also allows the materials be inspected nondestructively (without damaging the structure) and accurately (with 85% accuracy). This method allows the durability, structural integrity and extent of damages of these materials and structures to be evaluated conveniently and quantitatively.

ACKNOWLEDGEMENT

The authors wish to thank the Hong Kong Polytechnic Univeristy (G-YE27) for funding support.

REFERENCES

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