ABSTRACT

The effectiveness of use of fiber reinforced polymer (FRP) composites as externally bonded reinforcement for the rehabilitation of deteriorating and under-strength concrete components depends intrinsically on the integrity of the FRP and the bond between FRP and the concrete substrate. It is thus necessary to inspect the rehabilitation for defects during and immediately after application and through the service-life of the rehabilitated structure. Exigencies related to the field necessitate the development of rapid, yet accurate, tools for quantifying defects and following their progression. This paper reports on the results of an investigation into the use of Infra Red (IR) Thermography as a means of inspection and assessment of defect progression. It is shown that IR Thermography is extremely effective and can enable identification, quantification, and assessment of damage progression.

KEY WORDS: IR Thermography, FRP rehabilitation, concrete, defects

INTRODUCTION

Although the use of fiber reinforced polymer (FRP) composites is widely accepted as a means of rehabilitating deteriorating and under-strength concrete components and numerous guidelines and specifications have been developed for the design of such systems there is still a critical lack of data and understanding in three areas related to (a) inspection, (b) defect assessment, and (c) prediction of service life and durability. This necessitates not only that the defects be identified using a rapid and accurate method of non-destructive inspection (NDI), but that the method also enable tracking of the defect and assessing its criticality through the service-life of the structure. This intrinsically needs both the quantification of defects and the tracking of their extent as a function of time, load, environment, or combinations thereof.

With the exception of visual inspection, most NDE methods have a common characteristic in that they involve the application of a specific excitation to the structure and the measurement of the response of the structure to that excitation. Since a comprehensive review of NDE methods applicable to FRP rehabilitated concrete was recently published by Kaiser and Karbhari (2004) a summary of methods will not be repeated herein. However, it is important to emphasize that despite the wide range of available NDE methods, ranging from use of acoustic and ultrasonic excitation, to dye penetrants, radiography, thermography, eddy currents, microwaves and ground penetrating radar, optical means, conventional and advanced strain measurement techniques, modal analysis and load testing, only a small number can be effectively used in the field. Further, of these, only a smaller subset has the potential to be used effectively for identification, quantification and tracking of damage progression using field-applicable tools. To date only visual inspection and acoustic impact testing (coin-tap testing) have been used, albeit on a qualitative rather than a quantitative basis. Methods such as Infrared thermography which have been used fairly successfully in the aerospace arena however have significant potential for application to cases of FRP rehabilitated concrete. Previous research (Levar and Hamilton, 2003; Starner et al. 2003, Ghosh and Karbhari, 2004) in this area have to date largely been qualitative in nature and have not focused on progression of damage beyond a very superficial level.

The principle of IR thermography is to input heat energy onto the object being inspected and measure the resulting discontinuity in IR flow. The ability to measure differences in heat makes infrared cameras extremely valuable diagnostic tools. The ability to cover large areas rapidly without significant support equipment and without disruption of use of the structure as well as the ability to be used even in areas with restricted access...
make this method superior to other competitive methods for rapid inspection of concrete structures rehabilitated with composites. The technique is however new and requires further experimental investigation in order to develop it from a primarily subjective method to a precise one for defect detection and assessment. What is seen in an IR image is not an optical, but a thermal, image mapped in colors taken at an instant in time. A defect inside an object is in continuous thermal interaction with its surroundings and therefore, the size and visibility of a defect can change very quickly with time and eventually if delayed enough the area reaches thermal equilibrium with the surrounding and the defect can be completely obscured. This time-sensitivity can lead to misinterpretation of the extent or even existence of defects.

This paper reports on an investigation into the use of IR thermography as a means of non-destructive evaluation of FRP rehabilitation on a large scale deck-on-girder system.

**TEST DETAILS**

In order to ensure that the configuration and condition used in this study were similar to those that would be seen in the field, all tests were conducted using a model, three-girder–two-bay bridge specimen which was being used a proof-test for the study of FRP rehabilitation of concrete. Thus, tests were conducted on a specimen of scale and configuration similar to that which would be found in the field. Although all tests were conducted in a controlled laboratory setting, the placement and access available to the IR-thermography camera and operator were also similar to that available in the field with positioning of the camera being controlled only by manual means or through a temporary wooden scaffold.

The test specimen was a three-girder-two-bay bridge deck specimen (shown schematically in Figure 1), designed and fabricated in accordance with the California Department of Transportation Bridge Design Specifications (BDS). The center-to-center spacing between longitudinal girders was 1680mm (5.5') and the assembly consisted of a slab with 152mm (6") depth, and girders having a total depth, including the slab flange, of 559mm (22") and a width of 203mm (8"). The deck assembly had a total longitudinal span of 3600mm (12'4") including overhangs of 607mm (24") on either side of the edge girders. Details related to structural assessment are given in Ghosh (2006).

The bridge-deck specimen was monotonically loaded at the longitudinal mid-span by patch loads 1.83 m apart representing tires under increasing load and cycled at predetermined levels to check for stability until a load equivalent to 75% of transverse steel yield at which point the slabs underwent cracking and deterioration warranting rehabilitation. The structure was supported on load cells placed at the end of each girder. Carbon fiber reinforced composites in the form of wet lay up laminates and prefabricated strips were externally bonded to the deck soffits (one system per soffit) for purposes of rehabilitation (Ghosh, 2006). IR thermography was used to inspect the section rehabilitated with prefabricated strips, and hence details related to only that side are reported in this paper. The FRP rehabilitation program consisted of a single layer of pultruded strip of 101.6mm (4.0") wide repeated every 381mm (15") center to center in both longitudinal and transverse direction. The strips were of Tyfo UC type bonded with a Tyfo TC epoxy adhesive.

After completion of the rehabilitation, the specimen was loaded under monotonically increasing loads with cycling at periodic intervals. The cyclic loading consisted of a reduction of load to levels of 11kN (24kips) and
0kN (0kips) followed by an increase to the next higher load level. Thermographic images were taken at both the 0kN and 11kN levels to enable assessment of the rehabilitated specimen and to detect the gaps and cracks that might close as load was released. Thermographic images were then used for this research through an orderly study in order to investigate and quantify the presence and growth of defects and to enable the assessment of thresholds of criticality.

Active thermography was used for this experiment with the excitation being provided by a pair of xenon flash lights. The cross sectional dimension of the heat box on this particular instrument is 320mm by 240mm and therefore a number of shots were necessary to cover the area of interest within the experimental specimen. In this experiment, since only one layer of composite was used, a sampling frequency of 60Hz (60 frames per second) was chosen based on a series of calibration tests to ensure that no important data was missed during the thermal interaction. The duration time (which is the time period during which image capturing occurs and adjustment of which allows the heat to penetrate to a desired depth of the object being tested) used in this research was set at 10 seconds. A test done at 60Hz sampling frequency with a 10-second duration time yields 600 images. The use of large number photos decreases the possibility of missing a defect partially or completely but increases the level of effort to ensure the catching of effects due to very gradual and unnoticeable changes in thermal intensities from one image to another. The gate is a secondary time frame nested inside the main duration time. All of the photos in one particular gate are superimposed and shown as one single image. For the purposes of the current research 20 gates were used. Figure 2 shows a schematic of the FRP strips and areas over which IR thermography was conducted. An aggregation of the thermographic images for the entire component is shown in Figure 2.

RESULTS AND DISCUSSION

Once thermographs were taken the images were assessed using AutoCAD (for aggregation of images) and Matlab (for data interrogation) as shown in the flow-chart in Figure 4. It is noted that a defect and its surroundings are exposed to a specific amount of energy causing both to start raising temperature with different rates depending on their heat capacities, C, the amount of energy required to change the temperature of a unit mass of an object by one degree Celsius. The defect and its surrounding will then reach a transient equilibrium at one or two points of time which are called nodes. After the two objects cool down at rates which are functions of their thermal diffusivities (stage B in Figure 5) The cooling process continues until the change in slope is negligible (<5%) (stage C in Figure 5). Images taken at stage A, i.e. data from the first few gates are not suitable for analysis because the temperatures are still increasing. Images at stage C are also not suitable because defects can not be distinguished from the bulk due to establishment of thermal equilibrium. Therefore, data from stage B, where the temperature difference between defects and their surrounding is maximum, is used. In order to
select the optimum gate number (or time window) at which defects would distinguishable, all 20 images from 20
gates of a shot with obvious defects were assessed in terms of thermal intensities along a single line of reference
and the variation of thermal intensity as a function of length was then plotted at all 20 gates using a single
coordinate system. As seen in Figure 6, the response from gates 11 and 12 show the sharpest differentiation at
the boundary between the bonded and disbonded regions. Based on this measure, gate 12 was selected as the
basis for further analysis. It is noted that at higher gate numbers the material approaches thermal equilibrium
which is eventually attained at gate 19, at which point IR camera is unable to differentiate between the intact
material and a defect.

![Figure 5: Heat transfer profile of two materials with
different thermal conductivity](image)

![Figure 6. Representation of thermal intensity as a
function of position along the selected line](image)

Normalisation of raw images to a common baseline was necessary due to occurrence of one or a combination of
the following conditions: (a) Heat from the flash used for region affects the image taken subsequently in an
adjacent region both due to overlap and to thermal conductivity of the carbon fibers, (b) Change in
environmental conditions can cause an overall change from image to image, (c) A defect can appear to have
different severity in two different images if the background temperature changes from one image to another.
Three representations of image data were prepared at each load case. The first representation shows the raw IR
image after normalization without any further manipulation. This lay out helps to pinpoint the areas with
possible anomalies. At this level, the possible defects can be selected only based on changes of relative
brightness of the images, and hence it can not be determined with a high degree of assurance whether or not an
abnormality is really a defect. More information is required for a valid assessment about any of these areas. The
second representation depicts a contour map plot and is used to separate the areas with differing thermal intensity
and provides approximate location and extent of possible abnormalities. However, a wide range of data still falls
within each color band which could result in missing a defect. In addition, the image still does not show
sufficient differentiation resulting in one possibly missing a defect. To get around these difficulties and
ambiguities the threshold of failure was introduced. The threshold of failure is defined as the minimum thermal
intensity at which it is certain that debonding has taken place. The threshold of failure of this experiment was set
at 10% above the baseline which turned out to be ~135 on the 256 Gray Scale. The numerical value of the failure
threshold was obtained by comparison of the collected information of visually detectable defects at the 210k-0k
load stage with the intensities of the same regions at the baseline intensity. A Defects-only contour plot is the
final representation used in presenting defects with cleared-cut boundaries and also eliminating insignificant
effects that cause formation of distractive signals and false indicators. It is done by setting matrix elements
smaller than the threshold value equal to zero in the assembly matrix. Another unique application of this lay out
is its use in monitoring of structures through autonomous means to pinpoint defects with a high level of
accuracy. This can be done by projecting the lay out over the surface of the structure being assessed such that
changes can be easily identified. This facilitates the task of field monitoring significantly. Typical defect-only
plots for the some load stages are shown in Figures 7(a) and (b), clearly indicating the change in intensity
resulting from defect initiation and progression. The load level is representative of the cycle at which the thermograph was taken, i.e. 150-24 represents the cycle having a maximum of 150 Kips but taken on the unloading cycle at a load of 24 kips.

A global assessment can be made by plotting thermal intensities as functions of the length of the entire strip along slices on the left, right and middle of each strip. Figure 8 show an example of this indicating specific types of defects identified by level of intensity. The graph show the location, extent and the load stages at which each defect started to form and ultimately the defects that resulted in complete failure of the structure. This particular case shows that a small edge debond formed at load stage 150k-0k and grew as load increased to 170k-0k and 190k-0k but at the load stage at 210k-0k it dropped in intensity because the sustaining load was removed and consequently the debonding gap was closed. Another location further down the strip indicates that two defects formed at two different locations and load stages, grew with load increase and merged together to form a full through-width defect that resulted in complete failure of that region of the rehabilitation system. Local spikes that are extremely sharp are indicative of fiber rupture. Once anomalies are globally identified and tagged, they can be assessed for criticality and the rate of extension. Figure 9 shows a specific region of interest (ROI #14) in which three defects were initially seen at 130k-24k load stage. The fourth emerged later at the170k-24k load stage on the left side of the strip at about the time when the other defects merged thereby increasing stresses on a local region. Eventually a full through-width defect emerged at 210k-0k stage by growth and joining of all four individual defects resulting in a debond that covered nearly 50% (by area) of the strip in ROI#14. An assessment of the number of defective pixels at each region of interest over the loading spectrum can be used in prediction of IR responses emitted at load stages of interest. Considering ROI-14 where a through-width defect is formed, the process can be used as in Figure 10 to show progression with load in a quantifiable way. The plot of this ROI together with its IR images at the last two load steps is shown in Figure 10. It can be seen that although the IR image at the 190k-24k load step does not show any visually noticeable change in thermal intensity it in fact has 12 times as many defective cells than at the 130k-24k load stage. The study of such statistics could enable determination of threshold for initiation and progression. Further research to create defect maps for use in inspection is underway.

SUMMARY

IR Thermography enables a rapid inspection of FRP rehabilitated concrete components and the data gathered from the intensity maps provides a sufficient basis for the identification and quantification of damage. In addition, with the use of calibration, normalization, and enhancement procedures it is possible to follow the progression of defect growth and damage as a function of time. This is validated in this paper in terms of
increasing load. Further developments in defect maps are underway to develop this into a standardized and efficient technique for field NDE.

Figure 8. An example of sliced strip analysis

Figure 9. Progression in ROI #14

Figure 10. Plots of ROI-14 together with its IR images at the 190k-24k and 210k-0k load steps.

REFERENCES


