
Detection of air blisters and crack propagation in FRP strengthened concrete elements using infrared thermography

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ABSTRACT

This paper explores the possibility of (i) detecting the extents of air-voids between the bond-line of advanced composite materials (FRPs) and concrete substrate and (ii) predicating crack initiation and propagation in a reinforced concrete (RC) beam at early stage of failure. Both studies have been carried out successfully using Infrared (IR) thermography.

The artificial blisters (air-voids) with controlled sizes, embedded between the interface of FRP and concrete, were detected by the IR thermography remotely up to 20 metres away. The RC beam, which was initially at pristine condition, was subject to continuously static or cyclic loading tests. The preliminary results show that the damaged region of the RC beam, partially strengthened by glass fibre reinforced polymer (GFRP), which was covering the cracks, was clearly identified using an IR thermal imaging system. The anticipated failure plane was proven to be identical to the actual failure of the test beam.

Keywords: Bond-line, Advanced Composite Materials, FRP, Crack Initiation/Propagation, Infrared (IR) Thermography, Glass Fibre Reinforced Polymer (GFRP), Static/Cyclic Loading, Anticipated/Actual Failure Plane

1. INTRODUCTION

1.1 Forward

It is generally accepted that care and maintenance of the infrastructure globally is a key issue of the new century and a major challenge in the current decade. The construction materials used in infrastructure can often be regarded as at different stages of integrity or distress, which could be due to: (i) prolonged period of use, (ii) over-loading at or beyond serviceability limit, (iii) flawed initial design, (iv) poor workmanship and/or site supervision and (v) aggressive environmental or chemical attacks. The recent report on the state of the Nation's Infrastructures in the United States by the American Society of Civil Engineers estimates a remediation and retrofitting cost of US\$ 1.3 trillion (\$1.3 x 10¹² or approximately £915 billion), ASCE (2001). Similar surveys elsewhere indicate comparable costs of 5 billion per annum for the infrastructure in the United Kingdom, NCE (2001).

In many cases, demolition and reconstruction can be impractical, resource intensive, socially disruptive and environmentally unacceptable. Hence, the alternative may remain to repair, strengthen and maintain the existing structures and the built environment. Every retrofitting and upgrading activity should be preceded by an appropriate material integrity/distress evaluation for a meaningful and cost-effective outcome. Therefore, with such an increasing need in the construction industry, the non-destructive testing (NDT) techniques, such as IR thermography, are being developed for use as predictive and preventive maintenance tools, Hu (2002).

1.2 Significance of Current Research

The research is intended to develop a robust and reliable inspection procedure to monitor the damage in building, bridges and other infrastructures. This will help the practising engineers (i) assess the structural performance (ii) verify quality assurance in final products and services, and (iii) make decision in whether to take preventative strengthening and/or pre-emptive maintenance action, or allow the structure to become dysfunctional.

2. EXPERIMENTAL PROGRAM

2.1 Case Study I – Detection of Blisters

2.1.1 Insertion of blisters into CFRP and substrate interface

The blisters were modelled using rings of 1mm deep, cut from plastic piping, and embedded between the interface of Carbon Fibre Reinforced Polymer (CFRP) and concrete specimen. The commercially available pipes had diameters of 16, 18, 20 and 30 mm respectively with negligible variation in respective diameters, see **Fig. 1**.

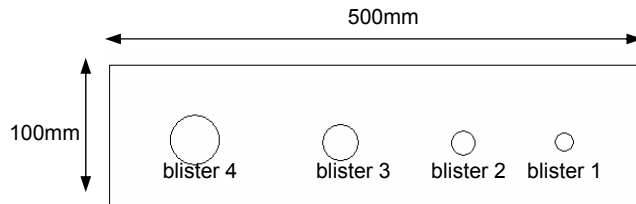


Figure 1. Illustration of embedded blister locations

Front Elevation

Note: Sizes of the bubbles, d: diameter

blister 1: $d = 16\text{mm}$, blister 2: $d = 18\text{mm}$, blister 3: $d = 20\text{mm}$. and blister 4: $d = 30\text{mm}$

After concrete surface preparation, the cut “blisters” were lightly pressed to the substrate before bonding the laminate and squeezing out unwanted natural air-bubbles with a “wall-paper” type roller. All bonded surfaces were allowed to be cured for at least one week before testing. **Plate 1** shows the actual visual image of composite specimens with the embedded artificial voids.



Plate 1. CFRP plate concrete specimens, where the artificial blisters are embedded between the interface of composite and substrate

2.1.2 Detection of blisters between CFRP and substrate interface

Under site conditions, the lamination of FRP may not create a perfect bonded surface with the concrete element due to existence of air voids or as a result of poor workmanship. Therefore, the effectiveness of the strengthening will be reduced. The relevant studies had been reported by Andreou et al (2000), Delpak et al (2001), Shih et al (2002).

The detection method has utilised the principle that air has lower thermal conductivity than concrete (or the cement paste). Therefore, a heated section of laminated FRP, backing to a blister (as opposed to backing to concrete either “solid” or porous), will remain warmer due to reduced thermal conduction. The thermographic images were

captured through an IR camera using Active Thermographic Approach (ATA), which required an external thermal perturbation to stimulate thermal distribution in the objects, Maldague (1993), Hu (2000). The ATA was achieved by deploying either radiant heat, from powerful electric light bulbs/lumps, or electric resistance heating elements attached to the bonded FRP surface.

The IR imaging equipment, AGEMEA Thermovision 900 SYSTEM, was of the typed available commercially with a minimum precision of $\pm 2\%$ at 30°C , and a resolution of 0.1°C .

Plates 2 (a)-(d) show the thermal image of the concrete beams, strengthened by CFRP materials, taken at different distances.

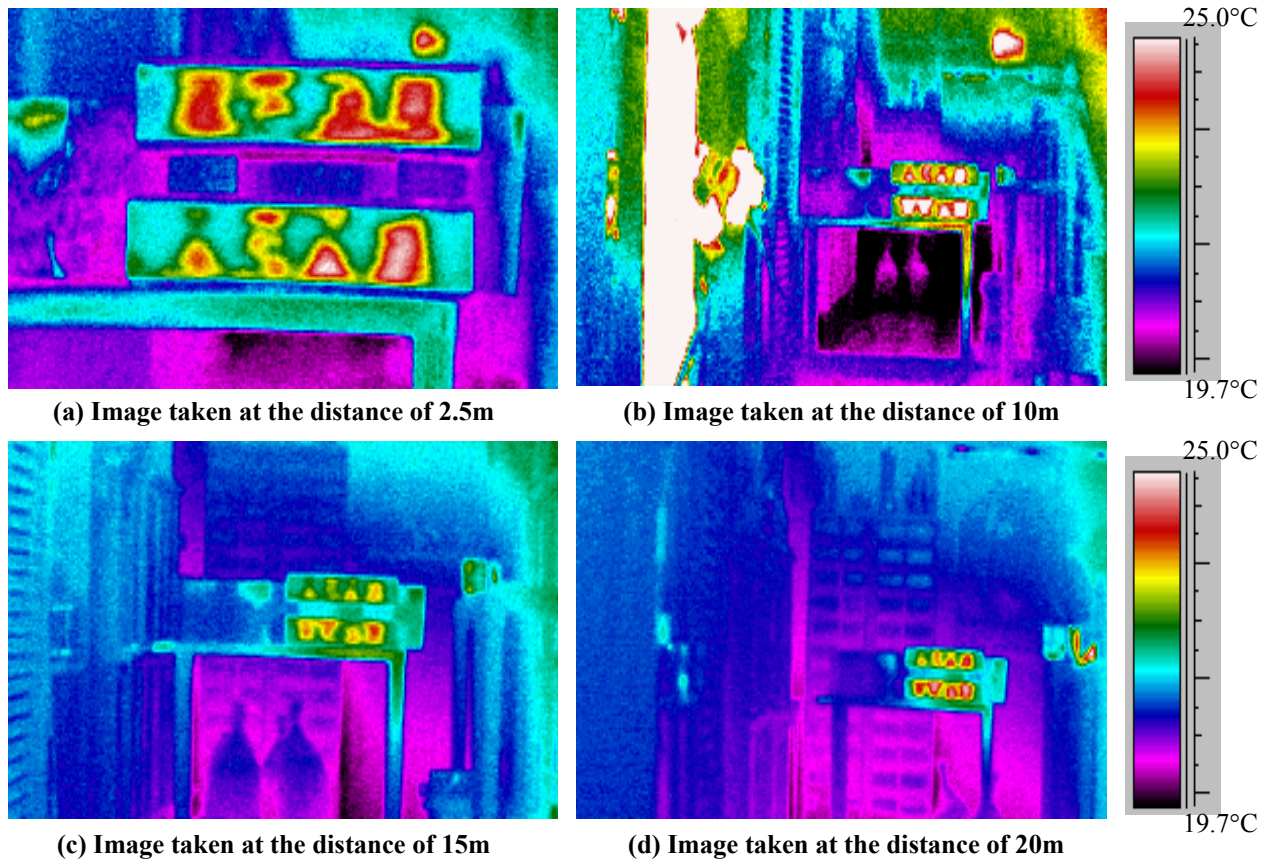


Plate 2. Thermal images taken at various distances for the concrete samples plated by CFRP (see Plate 1 for the corresponding actual photograph)

2.2 Case Study II – Prediction of Crack Initiation

2.2.1 Preparations of experimental set-up

A $100 \times 200 \times 1200$ mm concrete beam was reinforced in tension with three T10mm bars and laminated partially by Fibre Glass composite (GFRP) material. The GFRP sheets were applied through wet lamination using a two-part epoxy based adhesive. In addition, the reinforced concrete (RC) beam was placed on the jack and subjected to a 3 point loading condition, as shown in Fig. 2.

It was gradually loaded up to certain level of ultimate load and then continuously degraded through cyclic loading with a specified time period. In this study the load peak-to-peak amplitude was set to be 20% of static load. The frequency of vibration was set at 3Hz. The displacement readings at test beam center, were recorded after completion of each phase of static and cyclic loading sequence, see Table 1.

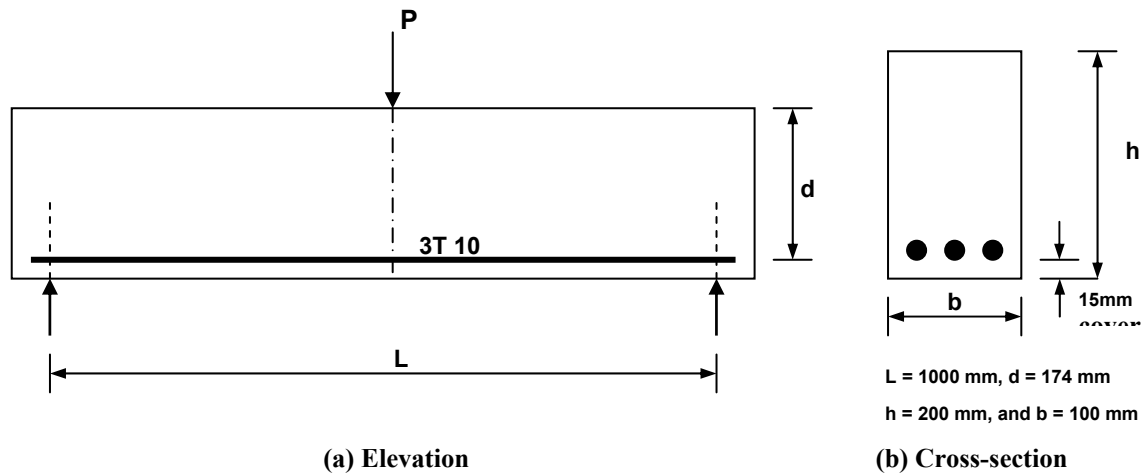


Figure 2. Configurations of test beams

Table 1. Displacements of 1.2m RC beam subjected to static and cyclic loading tests

Static load level (kN)	0	5	10	15	50	60	75
Centre displacement due to static loads (mm)	0	0.79	1.139	1.465	3.828	4.658	5.692
Cyclic Load Range (kN)	0	4.5-5.5	9-11	13.5-16.5	45-55	54-66	67.5-82.5
Centre displacement recorded after cycling load (mm)	0	1.09	1.190	1.551	4.245	4.984	Failure

2.2.2 Laboratory thermographic measurements

The thermal imaging system used for this part of work, CEDIP, for which the accuracy of the measurement performance is about $\pm 1^\circ\text{C}$, $\pm 1\%$, has a thermal sensitivity of 0.02°C at 25°C .

A series of thermal images were taken during each phase of loading in order to identify the potential failure area through various stages of thermographic monitoring process. It was hoped to record the generated heat through friction and fretting between cracks. The Passive Thermographic Approach (PTA) was therefore adopted for this study, Hu (2001). The natural heat was expected to be released at the locations where the defects exist, therefore, no additional thermal stimulation was needed.

3. THERMOGRAPHIC RESULTS AND OBSERVATIONS

3.1 Comparison of Blister Sizes from Measured and IR Images (Case Study I)

From the thermal image in Plates 2 (a) to (d), it is clearly possible to locate the positions of the artificial blisters where the areas with higher temperature existed. Even though the distance between the surface of samples and the transmission line of IR lens is increased up to 20m, the locations of air-voids covered by CFRP were still identified using the IR camera. If the bond line between CFRP and concrete (excluding blister locations) has no air voids, four

circular shapes or patterns with higher temperature are expected to be observed, see Fig. 1. However, the distorted hot areas have appeared and registered by images displayed in Plates 2 (a) to (d). This is due to the bad workmanship which resulted in the undesired thin gap around the blisters between CFRP and the concrete. This was confirmed after the removal of CFRP plates from the beams as seen in **Plate 3**.

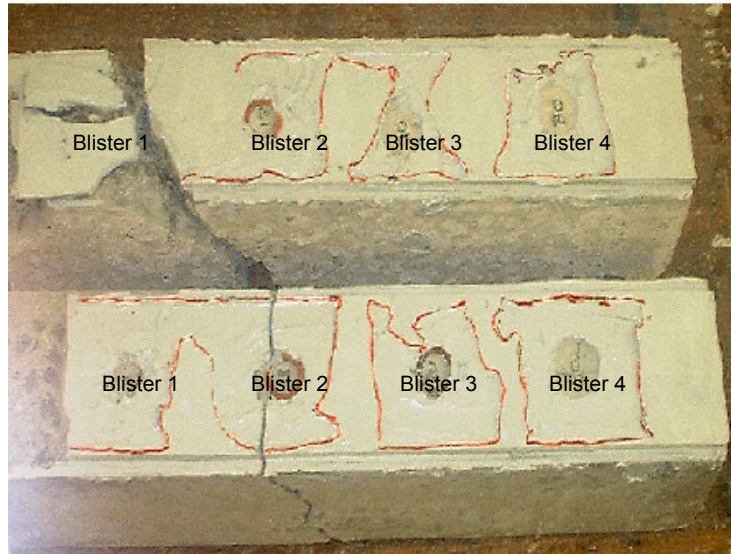


Plate 3.

Actual photograph of concrete samples, after laminated CFRP were artificially removed

(see Plate 1 for its corresponding photograph)

The specimens with the areas devoid of adhesive (highlighted by a marker pen), where the external heat flow supplied from the surface is supposed to be trapped, are clearly identified. By comparing the actual photograph shown in **Plate 3** with the thermal images represented in **Plates 2 (a) to (d)**, the potential of thermographic technique in detecting the defect locations in FRP strengthen specimens/ structures is justified.

3.2 Prediction of Failure Plane in RC Concrete Beam due to Cyclic Loading Tests

(Case Study II)

The continuous cyclic load action is expected to accelerate the formation of cracks, and hence initiate the generations of the heat through the friction at the areas, where the “discontinuities” are likely to be formed. Thermal images taken during the cyclic loading level of 45-55 kN is shown in **Plate 4**, where the area with triangular shape, highlighted by a white circle, indicates the dissipated energy due to the friction of the crack tips. From the image, it is predicable that the failure would take place within the region with the higher temperature and the possible failure plane would be about 45° along the triangular plane.

Plate 5 shows the thermal image of the test sample taken (fortuitously and) immediately, after the failure had occurred. It is observed that the actual failure plane shown in **Plate 6** is almost identical to the predicted one anticipated in **Plate 4**.

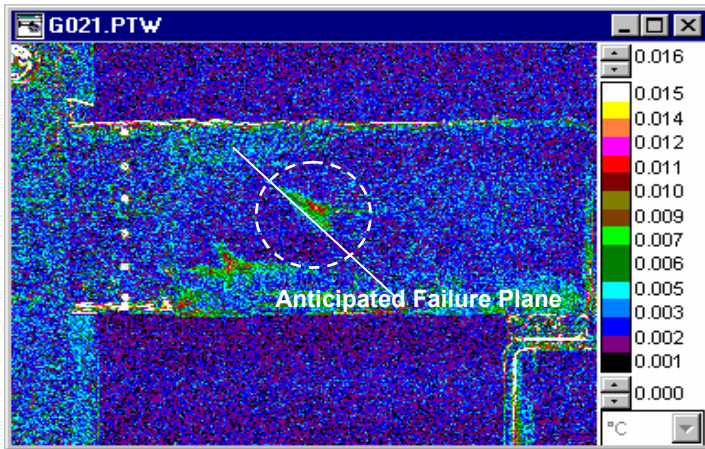


Plate 4.

Thermal image taken during 45 to 55 kN cyclic load range

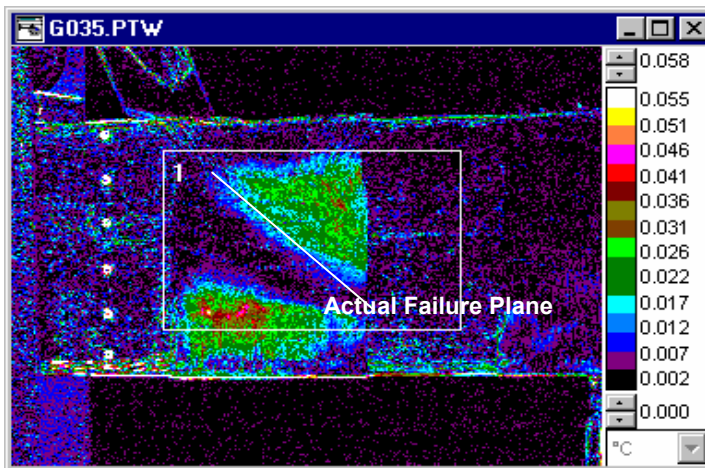


Plate 5.

Thermal image taken after failure occurred (at the cyclic load range of 67.5 - 82.5kN)

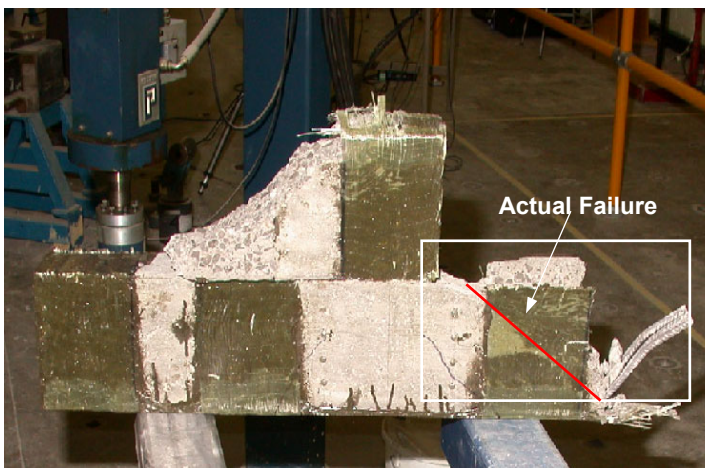


Plate 6.

Actual photograph for 1.2m concrete beam laminated by GFPR taken after failure occurred

4. DISCUSSIONS AND CONCLUSIONS

Through a number of controlled experiments in the current studies, the following were can be summarised:

Depending on the specifications of IR thermography, the blister locations between GFRP and concrete substrate could be identified remotely from a distance of up to 20m.

- Accurate detection of poor workmanship in wet-lamination and bonding processes of composite materials to concrete soffit was possible by using IR thermography.
- The size of the blisters could also be estimated if the distance between the IR thermography and the surface of the object is available.
- The dissipated energy (due to dysteretic action e.g. cyclic loading effect), between the potential failure planes, was identified using IR thermography. It can provide a □tell-tale□ warning of the damage present.
- The region of concrete beam, which had been strengthened by GFRP, was identified by IR thermography immediately prior to fracture due to cyclic loading.
- Subject to further trials, the current thermographic techniques can provide an unparalleled opportunity in locating concealed cracks as yet invisible to unaided eyes.
- It is clear the IR thermographic techniques can provide the maintenance engineers with both quantitative and qualitative information relating to the state of structural damage.

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