A study of full-field debond behavior of CFRP-reinforced concrete beams

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Abstract

The methodologies and results of a study on full-field debond behavior of CFRP-strengthened concrete beam composites under a quasi-static pull-off stress are presented. The methodologies used two approaches carried out simultaneously. The CFRP-strengthened concrete beam specimens were tested destructively with a modified pull-off test applied on the composites, and simultaneously tested with a nondestructive, full-field and non-contact infrared thermography method. The former pull-off stress (destructive test) ruptured the CFRP/concrete interface and initiated propagation of the rupture front from the loaded point. At specific displacement levels, the full-field temperature distributions (to represent and extent of rupture) over the surfaces were captured by an infrared thermo-imager. The extent of rupture, load level and displacement level were cross-plotted. The data showed an elastic-plastic failure model. The elastic-plastic failure process started from an initial elastic (large load increment, small rupture) state to a plastic (small load increment, large rupture) state after passing a yield point.

1. Introduction

The interfacial bond quality of the CFRP-strengthened concrete beams has been traditionally evaluated by destructive pull-off and hammer-tapping testing methods. Both types of tests have limitations as they can only be applied to localized areas and cannot be effectively used for large-scale inspection. These disadvantages can be resolved by using full-field infrared thermography (IRT) as a supplementary method which can reveal the unseen flaws in the composite material. The principle of the IRT method depends on the slower heat dissipation rate of an embedded flaw or a delaminated area compared with the well bonded areas of the composite. A number of recent studies (Maldague, 2001; Starnes et al. 2003; Maiehofer et al. 2006; Galietti et al. 2007; Hung et al. 2007; Poon et al. 2007; Benítez et al. 2007; Lai et al. 2009a,b,c) have demonstrated the usefulness of this approach.

The combined use of an IRT test with a destructive pull-off test demonstrates how non-destructive evaluation (NDE) and mechanical parameters of a material can be related. For NDE parameters, IRT images reveal the bond qualities in a full-field, non-contact and nondestructive manner indirectly, while a destructive pull-off test measures the bond strength (mechanical properties) directly. The latter provides information for structural designs and assessment of the built elements. However, data on destructive testing, such as pull-off tests, can only be sparsely obtained and cannot readily reveal the changes of the bond behavior during the rupture process before failure of the composites. The simultaneous use of IRT method during the application of the pull-off test can provide a better understanding of the intermediate debonding process to reveal the pull-off mechanism.

Integrating the NDE-IRT and mechanical parameters of the CFRP-concrete composites in the characterization of the debonding process using a quasi-static measurement (i.e. under a direct shear) and after exposing the specimens in various environmental conditions have been reported by the authors (Lai et al. 2009a,b,c, 2010) and Lai et al. (submitted). A new attempt on relating the NDE method with the pull-off test is reported in this paper. The pull-off test is commonly used to assess the bond strength...
between a CFRP with a concrete surface (ACI 4403R_04 part 3). However, the pull-off test is not amenable to reveal the possible defects that could present either at the CFRP-concrete interface, or within the bonding layer, or within the composite layers. Furthermore, the test cannot provide information on how the debonding process propagates during rupture from a pre-existing defect (Karbhari and Navada 2008). In addition, the NDE-IRT method can provide data from a much bigger and more representative area of the CFRP-concrete bond, which is not available in a conventional pull-off test method.

2. Experimental design and Materials

Four CFRP strips (brand names ‘SikaWrap® – 200C NW’, sized 100 x 700mm and 0.11mm thick) and the concrete beams (sized 100 x 120 x 900 mm) were bonded using two different proprietary epoxy resin systems (Sikadur® 300 and Tyfo® S), as shown in Figure 1. The epoxy and hardener were used at a ratio of 1 to 0.345 by weight. The mix proportion of the concrete used for casting the beams was: 1 (OPC ASTM Type I cement): 2 (river sand): 3 (10mm and 20mm natural crushed granite) with a water/cement ratio of 0.55. The average 28-day cube compressive strength of the concrete was 40 MPa.

Figure 1 The CFRP-strengthening concrete beam specimens

Before the CFRP strips (Figure 1) were laid on the concrete beam, the concrete surfaces were prepared and roughened by mechanical grinding. Then, a putty (brand name ‘Nittobo’) was used to fill up the surface concrete voids. The mixed epoxy resin was applied onto the concrete and CFRP strip surfaces at the same time, and they were held together in position until the epoxy was cured for 7 days.

A central notch (dimension 90mm deep x 100mm wide) was made by fixing a chamfered wooden plug at the centre of the beam’s formwork before the concrete was cast. The wooden plug was left and used to bridge over the wet CFRP strip when it was laid. The plug was then stricken off so that an empty notch space was left (Figure 2). During the pull-out test, the CFRP-concrete specimen was screwed fixed to a rigid steel frame and a steel rod (much larger than the width of concrete beam) was inserted to the CFRP at the notch area. Both sides of the steel rod were connected to a MTS loading machine. This design allowed the pull-out force to be applied perpendicularly to the direction of the CFRP-strengthened concrete beams without covering the bonded area which is the feature of the pull-off tests (ACI 440.3R-04). This allowed a better imaging of the IR camera.
3. Testing methods

3.1 The pull-off test

Before the pull-off test, a rod was inserted into the notch and loaded as shown in Figures 2a and 2b, to “pull out” the CFRP from the composite on both sides of the notch. The propagation of the two rupture fronts thereby simulated the actual field conditions in which the CFRP strips would be peeled off. In the study, monitoring of the force and displacement by the MTS equipment through the meticulous displacement control (0.5 mm per minute), and the extent and rate of rupture by the IRT data, provided information on the progression of the rupture process.
3.2 Infrared thermography

A FLIR quantum well SC3000 infrared thermo-imager (spectral range of 8 to 9 μm; 320 x 240 pixel array) (Figure 2b) was put next to the metal frame connecting to the MTS hydraulic loading system and the central notch of the specimen (Figure 2a). Two flash lamps (Bowens QUADX 3000) equipped with power packs were installed at 1m away from both sides of the specimen (Figure 2b). The temperature range of the thermo-imager was adjusted to span over approximately 20°C, with the lower temperature end adjusted to below the surface temperature of the specimen. This step ensured that the position of the specimen could be visualized in the thermo-imager before the flash. For each test run, the energy level and the flash duration of the flash lamps were fixed to be 3000J and 1/1400 seconds respectively. With this setup, the surface temperature of the CFRP was elevated approximately 0.7°C in the first moment when the surface temperature reached a maximum.

Before the pull-off test and at every 2mm after the application of the pull-off stress, the flash lamps were triggered to provide heat energy to the surface of the specimen. At this time, the pixel intensity of a small 5 x 5 pixel kernel within the CFRP strip area exceeded the prescribed maximum 8-bit value (i.e. 255 pixel value) and this triggered the thermo-imager to capture the 8-bit thermograms continuously for one minute with 25 frames per second, so that the cool down process was recorded. For each displacement increment (0.5mm per minute) of every test run, the above process was repeated, and the associated displacement and load levels were recorded. From these time-lapsed thermograms, the extent of full-field rupture front propagation was observed because the intact region cooled down at a much faster rate than the ruptured area.

In the time domain (i.e. changes in signals in z-direction in Figure 2a), one single defined thermogram was extracted out of the time-lapsed thermograms. This extraction depends on the measurements of time-lapsed thermal intensity between the hot and cold areas, from which maximum difference between these two areas was calculated (Lai et al, 2009a,c, 2010). The thermogram associated to this maximum is defined to estimate the geometrical shape of the rupture and intact areas in the space domain (lateral changes in x- and y-directions in Figure 2a). Then in the space domain, the boundary between the rupture and intact areas was defined by the steepest temperature gradient computed on the sample surfaces over the defects [Krapez and Cielo, 1991; Maldague, 2001]. Such computation may be processed with a number of algorithms, such as Roberts gradient [Gonzalez and Wintz, 1987], high degree approximation [Maldague, 2001], second order fit [Maldague, 2001], inflection point [Starnes et al. 2002; Lai et al. 2009b,c, 2010], and half-maximum [Lai et al. submitted]. In this paper, a pixel differentiation algorithm based on the second order fit method [Maldague, 2001] was adopted and is described as follows.

The pixel value P(x) in the x-direction extracted from the thermogram with the maximum thermal contrast was extracted and iterated in a computer program. An example is depicted in Figure 3. Each point in these P(x) was differentiated with respective to the x direction to determine the maximum gradient which is regarded as the position of the intact/ruptured boundary, at x’, as shown in Equation [1].

$$\frac{\partial P(x)}{\partial x} = 0 \text{ at } x' \quad \ldots[1]$$

where x = pixel cell; and P(x) = pixel intensity as a function of pixel cell.
Figure 3 Average pixel profile $P(x)$ along the x-x direction

The pixel cells from position $x'$ to the central notch represents the ruptured area, while those from $x'$ to the fixed end represents the intact area. The definitions of position $x'$ is graphically presented as the peak on each of the curves shown in Figure 4. With position $x$ at every row of $P(x)$ defined, the 8-bit pixel value over the CFRP surface was stacked, and transformed to a binary scale revealing the intact and ruptured areas (Figure 5). The number of pixels in each area was counted to calculate the rupture ratio, and presented as a fraction of the total number of pixels. This process was then reiterated over the entire CFRP strip for each quasi-static pull-off force.
Remark: the differential values were shifted with a constant factor for easy illustration.

Figure 4 Profile of $\frac{\partial P(x)}{\partial x}$ along the x-x direction.

Figure 5 Intact and ruptured areas represented by a raw 8-bit gray scale (top) and processed binary scale (bottom) after pixel differentiation method.
5. Findings

Figure 6 shows the binary thermograms (rupture and intact areas) of the four tested specimens. The thermograms were selected after processing with the thermal contrast and the pixel differentiation methods described above. For each thermogram, the right hand side is the loaded end, whilst the left hand side is the fixed end, and the illuminated area in Figure 6 represents the left part of the CFRP strip. These thermograms represent the full-field thermal distributions of the interfacial bonding layer at a particular state during the stress transfer. The white areas close to the central notch represent the ruptured part in the interfacial bonding layer, and the dark areas indicate the intact areas. With increase in load, the rupture increased and the rupture front propagated gradually from the loaded end towards the fixed end. The total rupture areas were then quantified and presented as a rupture ratio (defined as the ratio of rupture area to the total original bonded area) as a function of load and displacement in Figure 7. As the load and displacement increased progressively, the rupture ratio increased (Figure 7) from zero (total intact) to unity (total rupture).

For the propagation of the rupture front, the rupture ratio quantified by IRT increased gradually (linear) before the yield points (shown as the elastic region), after which the rupture ratio increased significantly (shown as the plastic region) especially. This shows that the CFRP strip debonded (or rupture) more rapidly after reaching the yield point. These yield points were at about 1.25kN which was about 60% of the pull-off strength (Figure 7). Beyond these yield points, the propagation of the rupture front (rupture ratio) increased more rapidly but also the measured load fluctuated in an irregular manner.

This observation can be explained as follows: when the load was smaller than the yield point, the CFRP strip was tightly bonded to the concrete surface and therefore the system behaved as an elastic material. Beyond the yield point, a large part of the CFRP strip was no longer attached to the concrete and the system behaved as a plastic material. This elastic-plastic behavior is further illustrated and substantiated in the load-displacement plot in Figure 8, in which the elastic and plastic behaviour are separated at the yield points at around 1.25kN.
Remark: the white area is the ruptured part and the black area is the intact part. Only the left part of the CFRP strip is presented.

Figure 6 Distribution of rupture and intact regions over the CFRP-concrete specimens at specific displacement levels using NDE-IRT method
Figure 7 Relationship between pull-off force of CFRP strip and rupture ratio determined by IRT

Figure 8 Load-displacement curve
5. Conclusion

A method combining the use of destructive and nondestructive tests was introduced to study the full-field debonding process of CFRP-strengthened concrete beam specimens. The methodology used a modified destructive pull-off test method, and nondestructive IRT method. The former measured the load and displacement levels during the pull-off process. The latter measured the extent of rupture via processing a series of time-lapsed thermograms with the thermal contrast and the pixel differentiation methods. Based on the joint measurement of load level, displacement level and the extent of rupture, the debonding can be described by an elastic-plastic model comprising an initial elastic region (large load increment, small rupture) to a later plastic (small load increment, large rupture) region after passing a yield point.

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References

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