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A Study of Using Full-field Thermographic Technique to Characterize the Shear Behaviour of Externally Bonded CFRP-concrete Composites

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ABSTRACT:

This paper present the results of a study on the behavior of CFRP-concrete beam composite when it is subject to a continuous shear stress using full-field thermography. Self-referencing thermal contrast and half-maximum methods were adopted to process the entire series of time-lapsed thermograms captured during the process. The distributions of pixel values contained in the processed thermograms were interpreted to represent the elastic, the elastic-softening, the elastic-softening-rupture and the softening-rupture stages experienced by the composite. These distributions were further analyzed quantitatively to evaluate the longitudinal rupture fraction and the effect of the applied shear stress on the extent of the ruptured areas. Based on these findings, the rupture areas were quantified and were found to increase significantly when a higher shear stress was applied. The information provided by the full-field thermographic data have potential to be used as additional data (tip of rupture, ruptured and softened areas) to supplement constitutive equations and bond-slip models in fracture mechanics.

1 INTRODUCTION

Fibre Reinforced Polymer (FRP) has become an important and widely accepted material to rehabilitate deteriorating concrete structures (Karbhari and Seible, 1999; Watson, 2000). The use of the FRP to repair and strengthen concrete elements has the potential to revolutionize traditional civil engineering structures. The polymers, especially carbon reinforced fibers (CFEP), are either applied to beams and slabs or are wrapped around columns to enhance the performance of the structural elements. The major functions and applications of CFRP are to enhance the resistance to shear and bending in concrete columns, beams and slabs (Chen and Teng, 2003; Teng et al. 2004), and to retrofit and strengthen damaged concrete bridges and structures. For these applications, CFRP strips are bonded to concrete structures using epoxy resins (ACI, 2004). The structural behaviour of the CFRP-concrete composite has been extensively studied using bond-slip fracture mechanics models (Nakaba et al. 2001; Wu and Yin, 2003) with direct shear tests. These models are developed by measuring the intermediate shear stress and strain along the loading axis simultaneously. The strain value is conventionally only a discrete measurement recorded by strain gauges laid on the CFRP surface, and is usually measured by a point-by-point fashion. Therefore, a full-field and non-contact instrumentation method for strain measurement is needed since it measures strain and debond distributions over the entire CFRP surface. A full-field strain can be measured by methods like digital image correlation or shearography; while full-field debonds can be measured by a thermographic method. This study attempts to use the thermographic method to characterize the rupture (as a

type of debond) and softened conditions which are related to the deterioration of the the direct cause causing strain over the CFRP surface.

The underlying principle of using thermograpy to analyze a CFRP-concrete composite relies on the presence of inhomogeneous delaminations contained within the composite material system, which reduces the heat diffusion rate when a thermal stimulus is applied. A few recent literatures (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. in press) demonstrate the values of using a non-destructive evaluation technique (NDE) approach for locating or quantifying delaminations embedded within the composites. This study attempts to further characterize the dynamic behaviour of the CFRP-composite upon the application of a progressive shear stress. This characterization is achieved by measuring (1) temperature gradient over the CFRP; and (2) ruptured ratios of the CFRP-concrete interfacial bonds using the thermographic method.

2 MATERIALS

Five CFRP-concrete composite beams were tested. The CFRP strips (brand name 'Nittobo', sized 60 x 200mm and 0.165mm thick) and the concrete beams (sized 150 x 150 x 350 mm) were bonded using a proprietary epoxy resin system (Sika 300^{TM}). The mix proportion of the concrete used for casting the beams were : 1 (OPC ASTM Type I cement): 2 (river sand): 3 (10mm and 20mm natural crushed granite) with a water/cement ratio of 0.50. The average 28-day cube compressive strength of the concrete was 39 MPa. The Sika 300 was mixed by in a ratio of 3-part epoxy to one-part hardener by weight.

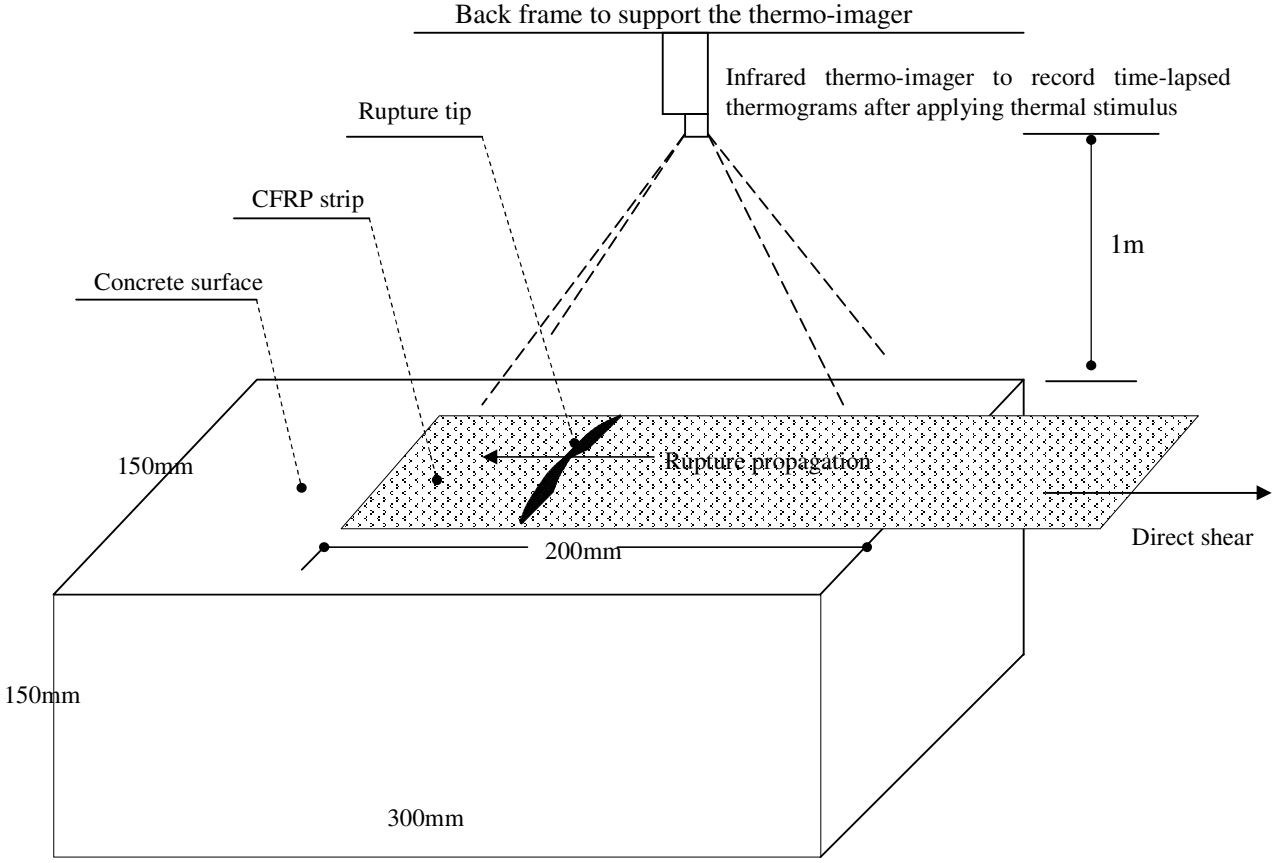


Figure 1 Setup of the thermographic inspection on a CFRP- strengthened concrete beam subject to direct shear

The surfaces of the concrete beam were first prepared and roughened by mechanical grinding before the CFRP strips were laid, so that a rough contact surface was simulated. Before application, the CFRP strip was cleaned and dried in air. Once mixed, the adhesive was applied onto the concrete and CFRP strip surfaces at the same time, and they were held together in position by dead weights until the adhesive cured. The schematic and picture showing the test setup are shown in Figure 1.

3 TEST AND ANALYSIS METHOD

The infrared thermo-imager used in the experiments was a FLIR Prism DS IR thermo-imager with spectral range 3.6 to 5 μm. Detailed descriptions of the thermographic procedures can be found in Poon et al. (2007) and Lai et al. (in press). Modifications to the procedures are briefly described as follows. Initially a baseline test run was carried out before a horizontal shear force was applied to the CFRP strip. A thermal stimulus was applied directly on the CFRP surface to heat up the specimens for 30 seconds. The thermal stimulus was a hot pack with a fairly constant and self-regulated surface temperature (40^0C). After which the stimulus was removed and immediately, time-lapsed thermograms were captured for another 30 seconds at a frequency of 25 frames per second. After the baseline test run, a horizontal shear stress was progressively applied on the loaded end of the CFRP strip through a direct shear system (MTS) until failure occurred. This shearing process was monitored with a meticulous displacement control (Δd = 0.2mm per minute). When a certain shear force level (approximately at an interval of 2kN after reaching 5kN) was reached, the above application of the thermal stimulus, and the thermograpy capturing procedures were repeated.

After the experiment, the time-lapsed thermograms were decoded to a sequence of 8-bit digitized and two-dimensional thermograms/pixel arrays through an analog to digital (A/D) process. This A/D process was controlled via the 'National Instrument™' hardware and a computer program developed under the LabVIEW™ and IMAQ™ environment. These arrays were then processed with a thermal contrast method.

For the analysis of the data, we adopted a self-referencing thermal contrast method (Shepard et al., 1999) to indentify the thermogram, out of all the thermographs of the whole time-lapsed series, for quantification of ruptured (debonded) areas. The method has the advantage of not requiring a prior recognition of fixed intact areas, as required in the common absolute thermal contrast method. The self-referencing method compares the thermal evolution curve of every pixel with a small kernel (sized 25 x 25 pixels) surrounding that pixel. The former is initially assumed as a delamination and the latter is assumed as an intact bonded area. If there is a continuous diversion between the thermal evolution curves of that pixel and the kernel at any time point, that pixel can be confirmed as a delamination, and otherwise as an intact area. Each delamination pixel thus possesses its own thermal contrast and this method is named as "self-referencing" because it does not require a prior recognition of fixed intact areas.

To cope with the dynamic situation of in the test described in this paper, the delamination-free baseline thermogram (at a state where no shear force is applied) over the entire CFRP strip was defined as the kernel (intact area). The size of this kernel (483 x 146 pixel matrix) was much larger and more representative than the 25 x 25 pixel kernel assumed in the self-referencing method. The thermogram for the quantification of ruptured areas was selected when the thermal contrast was at the maximum, as shown in the raw pixel profiles shown in Figure 2 and the thermal contrast (or pixel difference) shown in Figure 3.

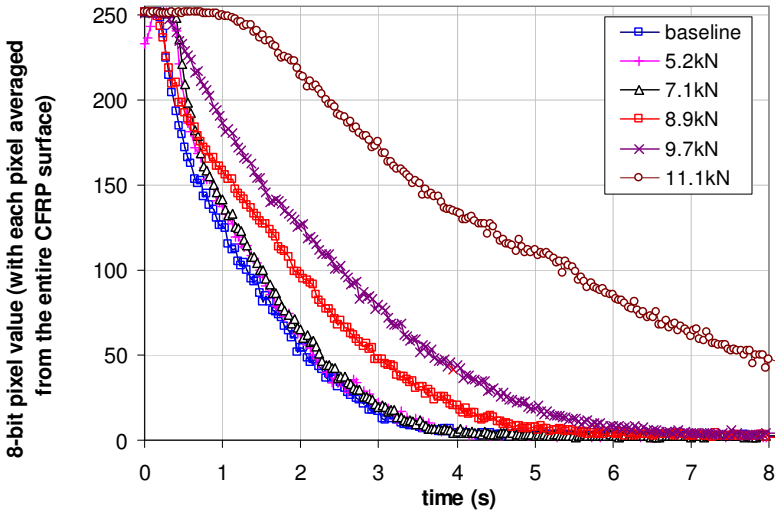


Figure 2 Time-lapsed thermal decay curve of the entire CFRP strip subject to different shear forces

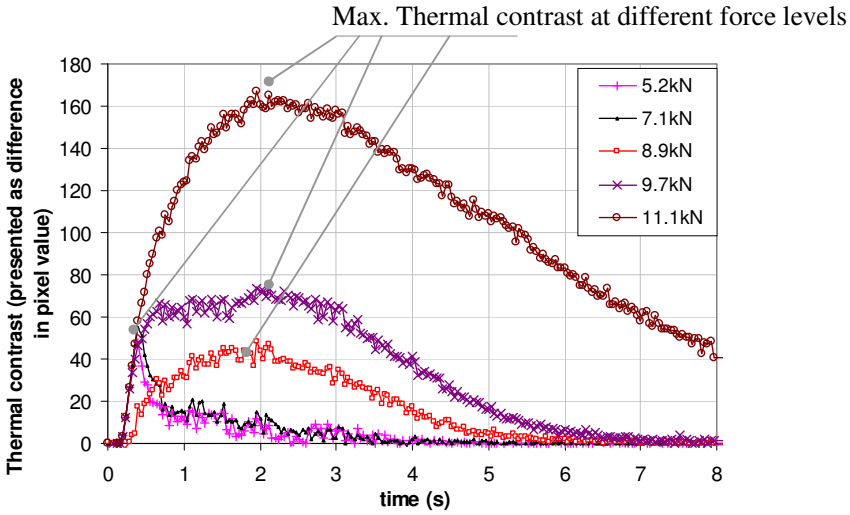
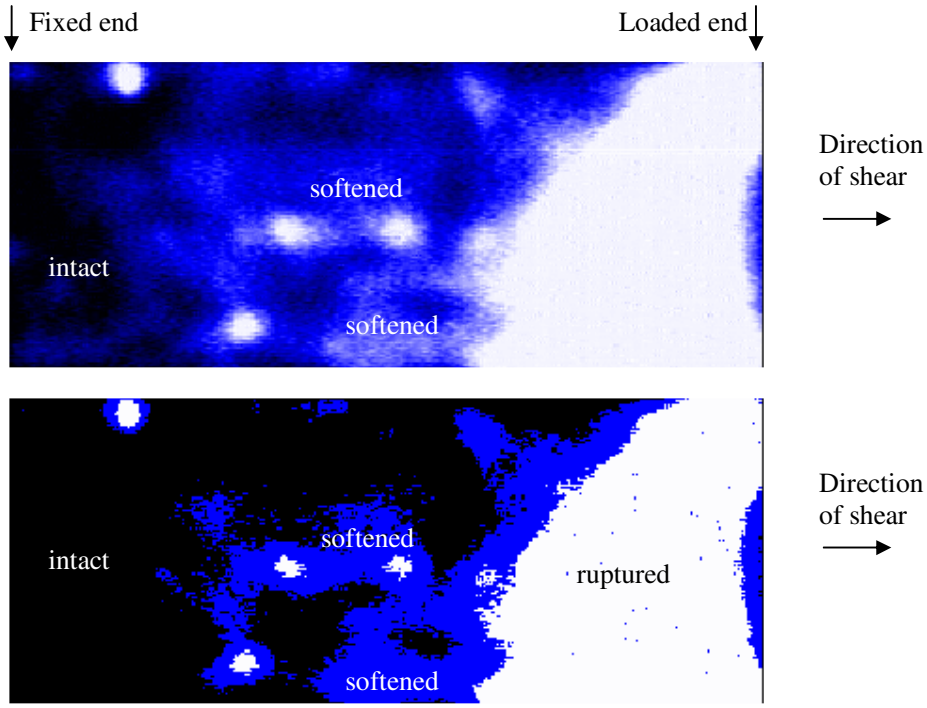


Figure 3 Thermal contrast of the entire CFRP strip subject to different shear stress levels

After selecting the thermogram derived from the self-referencing thermal contrast method, a fairly simple and direct half maximum approximation method (Maldague, 2001) was adopted. Each 8-bit pixel value (ranging from 0 to 255) over the CFRP strips was defined as ruptured or intact states. The half-maximum value (127) was assumed as the threshold. Below which the area dissipated energy quickly and is defined as **intact**; above which the area cooled slower and is defined as **ruptured** or **softened.** In particular the location with the highest and continuous pixel values closed to the loaded end represent the ruptured area, while those pixel values lower than this 2nd threshold and larger than the half-maximum is defined as being softened. Through these two thresholds, every 8-bit pixel value over the CFRP surface was transformed and categorized to a three-fold scale, which is zero (black), unity (gray) and two (white) representing the intact, softened and ruptured areas respectively (Figure 5). The number of

pixels in each case was counted and presented as a fraction of total number of pixels. This process was then reiterated over the entire CFRP strip at each quasi-static shear force.



Remark: the localized, small and circular/elliptical bright spots are flaws embedded within the interfacial layers

Figure 4 Thermograms in (top) 8-bit scale and (bottom) transformed binary scale

4 EXPERIMENTAL RESULTS

Figure 5 shows the thermograms in one of the five beam specimens. The thermograms were selected after processing with the self-referencing thermal contrast and the half-maximum approximation methods. For each thermogram, the right hand side is the loaded end, whilst the left hand side is the free end. These thermograms represent the thermal distribution of the composite at a particular state during the application of the shear stress. The white areas close to the loaded end represent the ruptured part in the interfacial bonding layer, whilst the black areas (pixel value = 0) indicate area with intact bond and the grey area represents the softened area. It is obvious that as the shear stress increased progressively, the area of rupture increased according to four different stages as defined in Yuan et al. (2004). These four stages are (1) elastic stage, (2) elastic-softening stage, (3) elastic-softening-rupture stage and (4) softening-rupture stage.

Initially, there was no sign of softening in the thermogram despite the shear stress reached to about 45% of the ultimate shear strength, as shown in Figures 5a. Therefore, the entire length of the interface was in an '*elastic stage*'. Later, when the shear stress was increased to 62% of the shear strength, a significant part of the interface became ruptured and the ruptured front continued to propagate towards the fixed end, as depicted in Figures 5b to 5d. In these figures, the areas close to the fixed end were still black in color and were in the elastic stage (the pixel

value in the thermogram was below the half-maximum). The above can be described as "*elastic-softening-rupture*" stage because all three stages were present in the same specimen. Finally, the "*softening-rupture"* stage was reached, where large areas of rupture and softened bond were observed, as shown in Figure 5e. Although the "*elastic-softening stage*" could not be exhibited in the collected data, it is believed that it should be present somewhere near the loaded end and at a stress level between 5.2 to 7.1kN as shown in Figures 5a and 5b.

This series of thermogram reveals qualitatively the full-range elastic, softened and rupture process of how a CFRP-concrete composite behave when it was subject to a continuous shear stress. To further describe this behavior quantitatively, an analysis of the longitudinal distribution of rupture areas over the composite at intermediate shear stress levels is required.

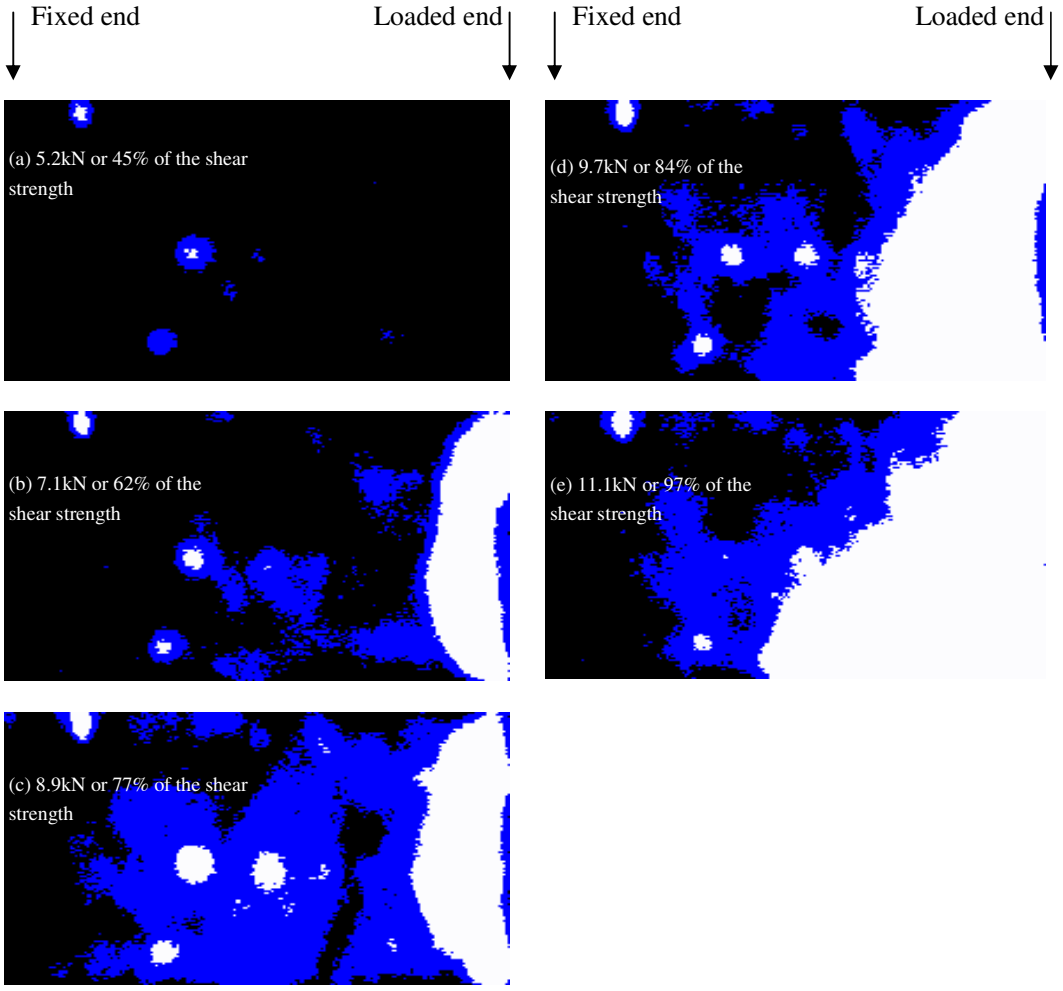


Figure 5 Thermograms showing the ruptured areas subject to different shear stress levels

Based on the two dimensional thermograms shown in Figure 5, a longitudinal distribution of ruptured area w.r.t. the entire areas is given in Figure 6. Similar to the above descriptions, a ratio equal to unity means that the CFRP was entirely ruptured and a ratio below 0.5 (half-maximum) means that the bond is still perfectly intact. A value between the ratios 0.5 to unity

represents a transition where the bond was softened. In all the five specimens, the width of this softened portion expanded when a higher shear stress was experienced.

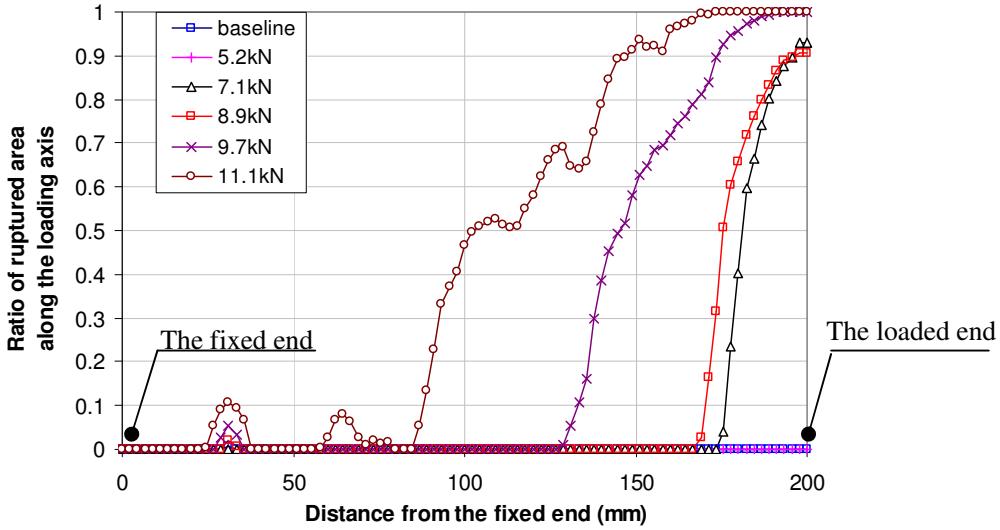


Figure 6 Longitudinal distributions of ruptured area w.r.t. entire areas along the loading axis

Figure 7 further demonstrates the effect of increasing shear stress on the ratio of ruptured areas. It can be observed that the near-exponential relationship implies that the contributions to the ruptured areas at higher force levels are more significant than at the lower shear force levels.

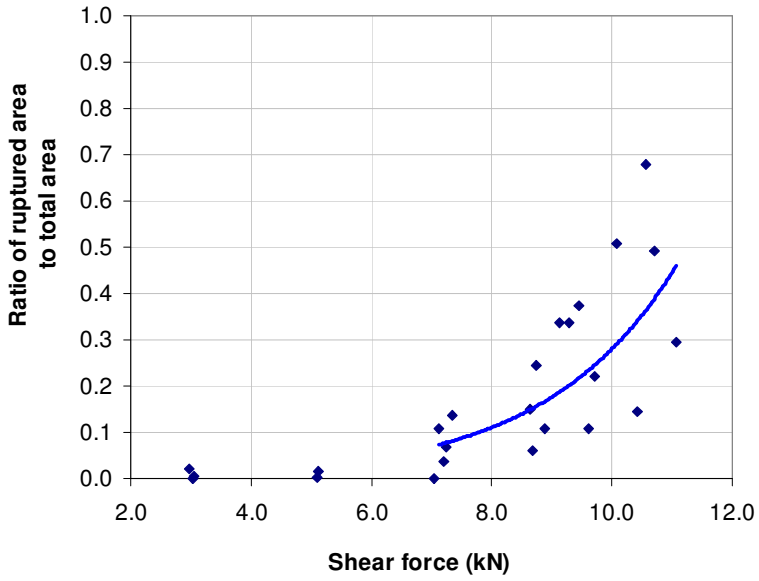


Figure 7 Effect of shear force levels on the ratio of ruptured area

5 CONCLUSION

Rupture and softened behaviour of CFRP-concrete beam composites were studied under the effect of direct shear by a full-field thermographic method. At different levels of shear stress, the elastic stage, the elastic-softening stage, the elastic-softening-rupture stage and the softening-rupture stage were characterized by the pixel distribution in the two-dimensional thermograms. The results presented in this paper demonstrate the possibility of using data obtained from the thermographic method to supplement the conventional bond-slip models and constitutive equations.

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References

ACI committee, Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete, 2004.

Benítez H.D., Ibarra-Castanedo C., Bendada A., Maldague X., Loaiza H., Caicedo E., 2008. Definition of a new thermal contrast and pulse correction for defect quantification in pulsed thermography, *Infrared Physics & Technology*, 51, 160–167.

Chen, J.F. and Teng, J.G., 2003. Shear Capacity of FRP-strengthened RC beams: FRP debonding, *Construction and Building Materials*, 17(1): 27-41.

Galietti, U., Luprano, V., Nenna, S., Spagnolo, L. and Tundo, A. 2007. Non-destructive defect characterization of concrete structures reinforced by means of FRP. *Infrared Physics and Technology*, 49, 218-223.

Hung, Y.Y., Chen, Y.S., Ng, S.P., Shepard, S.M., Hou, Y. and Lhota, J.R., 2007. Review and comparison of shearography and pulsed thermography for adhesive bond evaluation, *Optical Engineering*, 46(5), 051007.

Karbhari, V.M. and Seible, F., Design Consideration for the Use of Fiber Reinforced Polymeric Composites in the Rehabilitation of Concrete Structures, NISTIR 6288, Proc. NIST Workshop on Standards Development for the Use of Fiber Reinforced Polymers for the Rehabilitation of Concrete and Masonry Structures, D.Duthinh, ed., Gaitherburg, Md., 1999.

Lai W. L., Kou S. C., Poon C.S., Ng S.P. and Hung Y.Y. Characterization of flaws embedded in externally bonded CFRP on concrete beams by infrared thermography and shearography, *Journal of Nondestructive Evaluation*, in press.

Maierhofer Ch., Wiggenhauser H., Brink A. and Röllig M., 2004. Quantitative numerical analysis of transient IR-experiments on buildings, *Infrared Physics & Technology*, 46, 173–180.

Maldague, X. P. V., 2001. Theory and Practice of Infrared Technology for Nondestructive Testing, Wiley-Interscience, John Wiley & Sons, Inc.

Nakaba K, Kanakubo T, Furuta T, Yoshizawa H., 2001. Bond behavior between fiber-reinforced polymer laminates and concrete. *ACI Struct J*, 98(3):359–67.

S. Shepard, B.A. Rubadeux, T. 1999. Ahmed, Automated Thermographic Defect Recognition and Measurement, Nondestructive Characterization of Materials IX, American Institute of Physics.

Starnes, M.A., Carino, N.J. and Kausel, E.A. 2003. Preliminary Thermography Studies for Quality Control of Concrete Structures Strengthed with Fiber-Reinforced Polymer Composite, *Journal of Materials in Civil Engineering*, 15(3).

Teng, J.G.., Lam, L. and Chen, J.F., 2004. Shear Strengthening of RC Beams using FRP Composites, *Progress in Structural Engineering and Materials*, 6: 173-184.

Poon C.S., Lai W. L., Kou S. C., Tsang W. F. and Lai C. C., 2007. A Quantitative Study on Bond Behavior between Fiber-reinforced Polymer (FRP) and Concrete Interface Using Infra-red Thermography (IRT), Proceedings of the *First Asia-Pacific Conference on FRP in Structures,* International Institute for FRP in Construction, pp. 717-722.

Watson, R. Wrapping it: Fiber Reinforced Polymers – A Cost-effective Solution for extending the life of our Aging Infrastructure, 2000, ASTM Standardization News, Feb, 22-25.

Wu Z.S., Yin J. Fracturing behaviors of FRP-strengthened concrete structures, 2003. *Engineering Fracture Mechanics*, 70:1 339–55.

Yuan H., Teng J.G., Seracino R., Wu Z.S., Yao J., 2004. Full-range behavior of FRP-to-concrete bonded joints. *Engineering Structures* 26, 553–565.