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The application of infrared thermography for assessment of the condition of structural elements

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ABSTRACT: Infrared thermography (IRT) has been used widely for various applications in structural engineering as non- destructive evaluation of materials and structures. It allows diagnosing structural defects, testing effectiveness of thermal insulation in residential and commercial buildings and evaluating structural integrity of separate structural parts or whole structures.

The paper intends to review, analyse and classify current methods and principles of using infrared camera in assessment of structures and particularly assessment of different structural problems. It demonstrates benefits of non- destructive way of assessment structures and the basic principles behind the infrared thermography including some testing results.

The aim of the project is to investigate the applicability of the infrared thermography for assessing the distribution of plastic deformations and delamination problems for combination of FRP and other structural materials. It analyses existing experimental approaches and theoretical models for infrared thermography applications in this area. Applicability of the IRT for assessment of hybrid structural elements is discussed and illustrated on basis of conducted experimental work.

1 INTRODUCTION

Infrared thermography (IRT) is a remote mapping system which allows to create infrared images via absorption of infrared radiation as heat is distributed in object space with time. It allows to detect and to evaluate the invisible radiation emitted by different objects and imaging system converts infrared radiation into a visible image.

IRT has been widely used in many industries and fields like meteorology, environment, medicine, architecture and engineering. Depending on the field and specific research characteristics and requirements, application of the infrared camera and test procedures vary. In engineering IRT has been mainly used as a technique for non- destructive evaluation of materials and structures with a surface temperature as key parameter. In civil engineering industry particularly, it has been used for various applications including monitoring and evaluating condition of concrete and masonry bridges, composite elements and steel structural elements.

1.1 History and Development of IRT

The roots of infrared thermography go back to the year 1800 when Sir William Herschel performed experiments with sunlight and discovered thermal radiation- invisible light later called infrared. Twenty years later, Thomas Seebeck discovered thermoelectric effect. As a result, in 1829 Leopoldo Nobili invented thermomultiplier, which was detecting voltage difference between two dissimilar metals with a change of temperature. Later Macedonio Melloni was able to focus radiation detecting body heat from distance of 9.1 m by refining the thermomultiplier into a thermopile. It was able to determine slight differences and degrees of heat. In 1880 Samuel Langley used a bolometer, which measured change in electrical resistance.

First infrared image was produced by Sir John Herschel in 1840. It was done by using an evaporograph, which allowed getting differential evaporation of a thin film of oil. Initially IRT has been used for military purposes; the use of thermal imaging for non-military applications became a popular technique only in 1960s. First devices were slow to acquire data from detecting thermal patterns and had poor resolution. They were primarily used to inspect large electrical transmission and distribution systems. More reliable and durable portable systems to conduct building diagnostics and apply for non-destructive testing of materials were developed in 1970s. The introduction and development of focal- plane array (FPA) technology in the late 1980s has improved image quality and spatial resolution. Since then, the use of IRT technology has considerably increased (Fluke Corporation, 2009).

1.2 Theory behind infrared thermography

For most materials temperature increases when they absorb infrared radiation over a wide range of wavelengths. As object emits infrared energy proportional to its surface temperature, infrared camera converts thermal infrared radiation pattern into a visible image (Clark, McCann and Forde, 2003). Energy levels are illustrated by colour or grey patterns with electromagnetic spectrums of the images differentiated between shortwave (SW) (3–6 lm) and long-wave (LW) (8–12 lm).

To obtain and analyse IRT images an IR camera with changeable lenses and a computer is necessary. Infrared detector, which is core of the camera, absorbs IR energy and converts it into electrical voltage or current (Meola *et al.*, 2005). Many parameters for particular application and materials would dictate the specification of the infrared device and optimise testing procedures, which includes:

- emissivity of the monitored material,
- type of the infrared detector,
- field of view and resolution of the detector,
- relative heat transfer,
- separation between heat source and the object,
- separation between source and infrared detector (Gaussorgues, 1994).

1.3 IRT techniques

There are two thermographic techniques for non- destructive evaluation which are

- pulse thermography (PT)
- lock- in thermography (LT).

These two techniques can have variations depending on heating method or different processing algorithm. Pulse thermography is conducted by stimulating the object by a heating pulse and monitoring its surface temperature evolution during the transient heating or cooling phases. It can be done in two modes: transmission and reflection. Transmission mode is performed when infrared camera detects rear face or opposite to the heating or cooling source, which can be usually not accessible. Lock- in technique uses thermal waves with sinusoidal temperature modulation results. This system collects a series of images and compares temperature computing amplitude and phase angle of the sinusoidal wave pattern (Meola *et al.*, 2005).

2 APPLICATION OF INFRARED CAMERA IN ENGINEERING

2.1 Classification of the use of IRT camera

The overview of existing work could be summarised in following classification of the applications in accordance to the material being investigated. Three different areas have been indentified to describe the use of the IRT investigating defects in masonry and reinforced concrete structures; steel and composite structures. These areas with corresponding application are demonstrated below.

1. Masonry and RC structures
   - 1.1. Detecting cracks and cavities
   - 1.2. Estimation of micro-cracking damages in concrete
   - 1.3. Indentifying delamination areas in FRP strengthened concrete structures
2. Steel structures
   - 2.1. Register the heat released due to the plastic deformations during process of testing
   - 2.2. Delamination of FRP strengthened steel structures
3. Composite and hybrid structures
   - 3.1. Identification of debonded and delaminated areas under the surface and within FRP composite system.
   - 3.2. Determination of the extent of the defects between FRP layers and the structural elements

2.2 Application for structural NDT & E

IRT has been widely applied as NDT method in civil and structural engineering. It is very effective and useful method, as it can identify inhomogeneities in a range of materials and the structures from distance which could be helpful for a range of structural application. Also some of the materials like carbon fibres, aluminium, rubber and certain resins are difficult to investigate under traditional methods. IRT technique has been developed to provide reliable testing results for such materials. Since April 2002 infrared thermography has been added to Building Regulations in UK as a technique for assessment thermal insulation for new non-domestic buildings where cracks and cavities can be identified with a use of the IRT. As further development Clark, McCann and Forde (2003) investigated the use of IRT with the low ambient temperatures for identifying delamination areas in concrete bridge structures and the internal structure of masonry bridges with IRT.

An novel approach to estimate defect detection for non-destructive evaluation purposes of structural materials has been described by Meola (2007). Experiments on several specimens have been conducted to develop a cause/effect relationship allowing to predict the thermal contrast of the defect inside a certain material by including characteristics of the defect and of the host material.

Investigations about the behaviour of the GFRP under low velocity impact using infrared thermography have been conducted to monitor the opposite side of the specimens impacted with modified Charpy pendulum hammer by Meola and Carlomagno (2010). Analysis of the images demonstrated the change of the thermal phases from thermo- elastic to thermoplastic describing characteristics of the material. Infrared thermography was also used for NDT evaluation of specimens before and after impact. Extent of the damages was seen from temperature maps. Impact energy and distribution of it to material is explained by polymetric matrix of the FRP. As fibre reinforced polymers have low intralaminar strength, they experience low velocity impact delamination between layers occurs. These results are comparable with plastic deformation assessment described later in this paper.

In 2003 IRT inspections have been carried out by Levar (2003) on CFRP composites strengthening concrete beams before flexure and shear testing and during the test to determine the extent of the bond as loading progressed. To create a temperature differential various external sources have been used including heat gun, hair dryer, kerosene heater and etc. Four types of the bond loss have been investigated during the process of the loading. Verification of results was done by using acoustic sounding, showing that about 20% to 30% of the defects damages could be detected only with IRT technique.

3 APPLICATION OF IR THERMOGRAPHY FOR ASSESSING HYBRID STRUCTURES

Hybrid structures combine several materials like concrete and steel or FRP used for the construction of different structures; hybrid concrete structures generally taken as a combination of in-situ concrete with precast concrete. In this paper hybrid structures are described as combination of concrete or steel with FRP.

3.1 FRP and concrete

IRT technique can be applied to analyse defects in the connection between reinforced concrete beams and CFRP laminates used for strengthening (Donchev, et.al, 2010). During experiment a high resolution VarioCAM infrared camera was used which is capable of measuring temperatures from -40°C to 1200°C. Figures 1A and B demonstrate the position, size and shape of the defects introduced in the adhesive layer between laminates and concrete. The infrared image is obtained after applying of external source of heating via a heat gun on the laminate. The areas of increased temperature are allocated and proved to correspond exactly to preliminary introduced defects. Initial research conducted by IRT research team at Kingston University indicates that the temperature differences are due to reduced thermal conductivity between the laminates and the concrete at the area of the defects. It has been determined that
IRT technique is effective to investigate the condition of the FRP parts of structural elements, as well as condition of the underlying concrete and reinforcement.

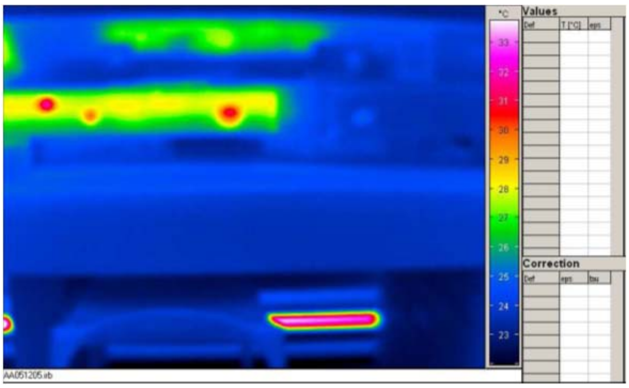

Fig. 1A Experimental set-up (left) Fig.1B Thermal image indicating defects (Donchev et.al., 2010)

3.2 FRP and steel

Recently IRT research team at Kingston University used IR thermography to identify delamination areas between steel and GRFP wrapping of shear wall. Figure 2A shows steel shear wall strengthened with GFRP being tested under quassi static loading in accordance to ATC-24 protocol. Steel shear wall consists of I-beams used as a boundary elements and thin steel infill plate, which was strengthened with GFRP wrapping on both sides. Specimen was loaded to a number of small and large sinusoidal displacements such as 0.2mm, 1mm, 3mm, 5mm, 10mm and 15mm. Each displacement has been applied for two or three cycles to record corresponding load. Visible delamination has been noticed for displacements higher than 3mm.

In order to estimate delamination areas between steel and GFRP with IRT technique, after each displacement external heat gun has been used. Figures 2A and 2B show debonding of the steel and GFRP wrapping which occurred when test was conducted. There is a very good correspondence between thermal image and actual image of the specimens, showing the location of the delamination area and its extent with a distribution of temperature differences.

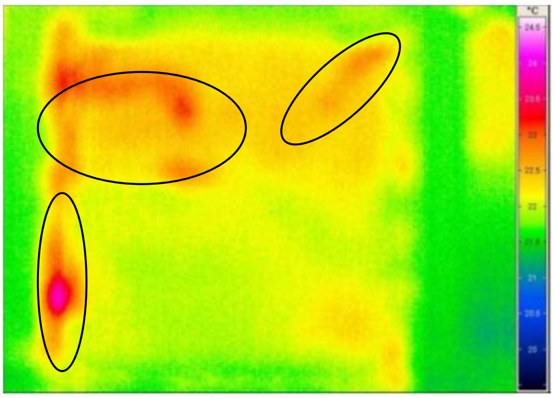

Fig. 2A Experimental set-up of strengthened steel shear wall Fig.2B Thermal image of hybrid shear wall

Similar trends and correspondence with actual images were noticed for higher amplitudes of quassi static testing as well. Figure 3A, B and C shows development of the delamination between GFRP wrapping and steel infill plate for 5, 10 and 15mm displacements of shear wall illustrated as black hatched areas. Delamination areas have been estimated as 26, 58 and 89 percents of the total area of strengthened infill plate for 5, 10 and 15mm displacements respectively. Estimated delamination has been compared with total areas of infill plate above 0.5 degrees for each specimen obtained from IR images for corresponding displacements. Results have an approximately 5-10 percents difference.

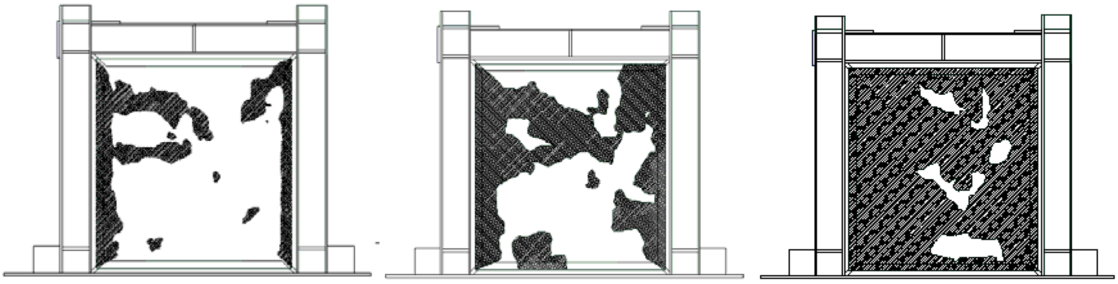

Fig.3A Delamination areas(5mm) Fig.3B Delamination areas(10mm) Fig.3C Delamination areas(15mm)

IRT is a fast method to determine and assess development of the delamination, however when analysis of IRT images is undertaken, it is important to take into accounts other defects occurring prior or during the test. The overview of existing applications and the additional experience gained by IRT research team at KU indicate clearly that IRT application for FRP strengthened and hybrid structural elements is a very promising technique.

4 CONCLUSIONS

On the basis of conducted research following main conclusions could be drawn:

- IR thermography is having wide range of applications as NDT method for assessing condition of structures, buildings and bridges.
- The application of IRT for hybrid structural elements is very important and allowing to assess crucial issues as delamination and its extent.
- Further development of IR applications will allow fast and cost- effective assessing of structures and structural elements.

5 REFERENCES

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