Multi-spectral near infrared NDE of polymer composites

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Abstract
Near infrared signals have been used to generate images of the internal structure of fibre-reinforced polymer and foam-filled honeycomb samples. Several different measurement configurations have been investigated, including the use of both modulated light-emitting diodes at discrete wavelengths and broad bandwidth illumination. It is shown that transmission through the samples is wavelength-dependent, and that artificial defects can be detected within polymer composite materials. In addition, wavelength-dependent properties have been used to detect changes due to water ingress into both composite materials and a solar panel structure, leading to a non-contact NDE technique.

Introduction
Infrared techniques have been used for some years for the non-destructive evaluation (NDE) of industrial materials. Thermography is one such technique [1,2,3], where an incident light source generates heat diffusion within a material. The thermal waves are then monitored as a function of time, typically using a camera with sensitivity in the correct region of the IR spectrum. This technique has been used extensively for the NDE of composite structures, and typically this is achieved using a pulse light source [4,5]. Information is then retrieved typically with a time or phase analysis [6,7]. Lock-in
thermography [8] uses an excitation that is modulated at a single frequency to provide an improved signal to noise ratio (SNR) when a tight narrowband filter is applied at that frequency on the output signal. More complex variations include multi-frequency lock-in thermography [9], or Pulse-compression infrared thermography [10].

This paper discusses a different approach to using near and mid IR signals – instead of generating a thermal wave, the aim is to directly image changes in the internal structure of samples by measuring the characteristics of the through-transmitted signal. Heating of the sample and thermal wave generation is minimised and not measured directly in this process, as the signal is received by direct optical transmission, and the thermal wave would take a much longer time to travel across the sample. The amplitude of transmitted energy at specific frequencies can give an indication not only of the presence of defects, but also changes in composition caused by degradation or changes in structure. This technique has often been implemented in the past by using a broad-spectrum source (such as a halogen lamp or heated filament source) with a hyperspectral camera, spectrometer or other form of detector. This is used to detect spectral changes in transmission [11]. Examples include assessment of wood quality [12], detecting inter-ocular tumours [13,14] and food quality inspection [15,16,17]. As in the case of thermography, the SNR of such measurements can be improved using lock-in techniques [18]. This is the approach used in the present work, where modulated NIR signals have been used in through-transmission to produce images of both glass fibre reinforcement polymer composites and foam-filled cellular structures. It is demonstrated that the use of multiple wavelengths allows features to be extracted from the data that would not be possible using a single illumination wavelength [16].

Samples and Experimental arrangement

Two samples were investigated. The first was a partially delaminated glass-fibre reinforced composite plate with a foam-filled honeycomb structure with thickness of 16 mm (Figure 1(a)(b)). The sample had 3.5 mm thick external composite plates on top and bottom surfaces containing biaxial glass-fibre fabrics impregnated with polyester resin. This enclosed the inner core hexagonal cell structure. The polyethylene terephthalate (PET) foam material was in the form of hexagonal honeycomb elements connected to each other with small joints (3D – CoreTM, supplied by 3D(CORE GmbH & Co. KG Oststraße 74 32051 Herford, Germany). Polymer was then added to fill the gaps between each hexagonal element to form the cell walls. The delamination existed between the outer fibre-reinforced external skin and the foam interior, and extended approximately 130 mm along the length of the 200 mm x 70 mm plate. It was not visible by eye. The second sample (Figure 1(c)) was a 10 mm thick glass fibre composite sample, with dimensions 100 mm x 100 mm. It contained a delamination approximately 3 mm from the top surface, which was of unknown extent into the sample, hence the need for an NDE technique to quantify this.
The bulk of the experiments were conducted using a NIR through-transmission imaging system. This used multiple fiber-coupled laser diodes as the source (MCLS pig-tail laser diodes from Thorlabs), and a photodiode (Thorlabs LnGaAs PDA10CS) as the detector. The sample could be scanned relative to the laser diode source/photodiode detector using a computer-controlled X-Y scanning stage, as shown in Figure 2. Experiments could be performed at one of four source wavelengths (\(\lambda = 852, 1064, 1310\) and 1550 nm) or on all together simultaneously by combining in a single beam the various lasers through beam combiners, see Fig. 2. In both cases, Lock-In was digitally applied on the photodiode acquired signal but in the multi-spectral case a modified Multi-Frequency Lock-In protocol (MF-LI) procedure was used to deal with multi-spectral analysis and signal-to-noise (SNR) improvement. The MF-LI measurement was implemented by using four different modulation signals, square wave at 3, 6, 12, 24 kHz, so that the wavelength selection and the LI filter were performed simultaneously on the same photodiode output signal by software with a minimum of hardware requirements. More details on the procedure can be found in [16]. The use of multiple laser diode wavelengths meant that multi-spectral information could be obtained for practical use in NDE. Data was collected at 1 mm intervals during a typical scan, over a scan area of 200 mm x 80 mm, and the received amplitude at the particular chosen NIR wavelength plotted as a function of position. Note that the use of laser diode sources for this measurement is not strictly necessary since also traditional LED sources could be used as well. In the experiments, the choice fell on the present source due to the possibility to easily connect and combine lasers outputs with optical fibers, simplifying the experimental setup.
Figure 2: Scanning system for through-transmission NIR imaging of composite samples at discrete laser diode wavelengths.

Additional information was obtained from a second measurement, where the wavelength-dependent NIR transmission properties at specific locations across the sample were measured using a spectrometer. This allowed information concerning changes in composition (such as the presence of water) to be investigated in a single measurement, and to allow optimal choice of a single LED wavelength for imaging purposes. Spectral data was recorded using a broad spectrum visible/NIR halogen source and a NIR spectrometer. The apparatus, shown in Figure 3, contained an optical lens system suitable for use at wavelengths of up to 2000 nm. A lens system focussed the energy from the 20 W halogen source, which emitted usable energy up to $\lambda = 2500$ nm, onto one side of the sample. A second co-axial lens system then collected transmitted NIR signals from the far side of the sample for input into an optical fibre/collection lens system, which transmitted the signal to an Ocean Optics NIR-256 NIR spectrometer (with a 900 - 2200 nm sensitivity range). The output was the relative amplitude of the through-transmitted signal as a function of wavelength $\lambda$. Note that the halogen source, optical path and spectrometer had their own spectral response, which had to be removed from the spectral data. This was done by first measuring the source characteristics after passing through a neutral density filter (optical density of 2.0), whose role was to reduce the maximum amplitude of the signal to within the same order of magnitude as that obtained after passing through the sample. This spectrum was then used to modify the response measured in through-transmission through the composite samples via a deconvolution procedure. This ensured that the process measured the correct material-dependent changes in spectral response.

Figure 3: Schematic diagram of the arrangement used for obtaining NIR through-transmission spectral characteristics.
Results

A. Foam-filled honeycomb composite

Figure 4 shows the results of a scan through the foam-filled composite sample. This has been plotted using both as-received amplitude data and in dB for a laser diode operating at $\lambda = 1064$ nm. Several features are evident, the main one being that transmission through the solid cell walls is greater than that of the foam material. In addition, it is also evident that there is less NIR transmission throughout the region of delamination (extending up to ~130 mm from the left-hand side of the image) and the undamaged area. It can be seen that the contrast is more obvious in the dB plot, where a region of more severe damage is visible.

![Figure 4](image)

*Figure 4: Images obtained from scans of the foam-filled composite sample at a NIR wavelength of 1064 nm. The results are shown for (a) as-received data, and (b) normalized data in dB.*

It is interesting to observe the through-transmission spectral characteristics, which were measured using the apparatus of Figure 3 for both the foam-filled region and the cell wall structure. The spectral results in both regions were very similar, but with more signal attenuation within the foam region. An example for the cell wall structure is shown in Figure 5. It can be seen that the spectrum is still noisy, a result of the high transmission loss within the sample. The dotted line shows that there is a peak response at $\lambda = 1000$ nm, with a decay in transmission amplitude with increased wavelength from this peak value. There is little transmission at NIR wavelengths above 1400 nm, and a rapid drop in signal at shorter wavelengths.

Scans of the sample were now performed at the four different laser diode wavelengths, and the results are shown on Figure 6 without the use of any filter or image processing algorithm. It can be seen from
these images that the best definition is obtained at $\lambda = 1064$ nm, with a lower SNR and image contrast at 852 and 1310 nm. No signal was recorded at $\lambda = 1550$ nm. This is all consistent with the spectroscopy results shown in Figure 5, indicating how important the choice of NIR wavelength is in such NDE imaging studies.

![Graph showing NIR spectral transmission characteristics.](image)

**Figure 5:** NIR spectral transmission characteristics in the 1000-2000 nm range for passage through the cell wall region. The dotted line represents an estimate of the smoothed spectral response.

![Images of NIR scans at different wavelengths.](image)

**Figure 6:** NIR scans of the composite honeycomb sample at four discrete NIR wavelengths – grayscale.

It is interesting to see the effect of unwanted contaminants on such samples. An experiment was thus conducted where the delaminated section was immersed in water, and the water drawn into the damaged area by capillary action. Water has a well-known NIR absorption spectrum, and this is shown in Figure 7. It can be seen that there are two main absorption bands, centered at approximately 1500 nm and 2000 nm.
nm. As will be seen from the spectrum of Figure 7, any water would be expected to attenuate NIR signals strongly at wavelengths $>1400$ nm, due to the presence of these absorption bands, but there is already little transmitted energy at these longer wavelengths even in the absence of water, as seen in Figure 5. Hence, any additional signal loss is expected to be minimal.

![NIR absorption spectrum of water](image)

*Figure 7: A sketch of the NIR absorption spectrum of water.*

The results of scans performed both before and after water immersion of the sample are shown in Figure 8. It can be seen that the contrast between undamaged and delaminated areas is reduced as water “index matches” the delamination to the composite. However, this occurs to a limited extent, and there is still a difference between delaminated and undamaged sections of the sample.

![Images comparison](image)

*Figure 8: A comparison of images obtained of the honeycomb sample in both (a) a dry state and (b) when water had entered into the delamination area by capillary action.*

The improvement in signal transmission in the presence of water can be seen clearly in the through-transmitted spectral data for the foam-filled areas, as recorded by the spectrometer set-up of Figure 3.
As shown in Figure 9, there is generally poor transmission in the absence of water, and there is little signal at NIR wavelengths above 1400 nm. In the presence of water, transmission levels increase, with more energy at the shorter NIR wavelengths.

![Graphs of through-transmitted NIR spectra](image)

**Figure 9:** A comparison of through-transmitted NIR spectra for the foam-filled core of the honeycomb composite sample when (a) dry and (b) containing water by capillary action.

**B. Imaging of a 10 mm thick glass fibre reinforced polymer (GRP) composite plate**

Experiments were also conducted on a 10 mm thick GRP composite plate, a photograph of which is shown in Figure 10. The fibres in such materials are highly scattering of NIR signals, but despite this, the lock-in technique allows signals to be recorded using a laser diode source at $\lambda = 1064$ nm. A delamination of increasing severity was introduced into one end of the sample, at a depth from the top surface of a few mm, and is visible in Figure 10. This was gradually enlarged by mechanical means, so that it penetrated further horizontally into the sample, and images produced at each stage to demonstrate that NDE of such samples would be possible. Scans were performed over an area 45 mm x 55 mm relative to the top surface of the sample.

![Photograph of a 10 mm thick glass fibre composite sample](image)

**Figure 10:** Photograph of a 10 mm thick glass fibre composite sample, with approximate dimensions 90 mm x 90 mm. The delamination can be seen close to the top surface.

Figure 11(a) shows a photograph of the sample with the extent of the delamination (estimated visually) marked by the irregular black line, and Figure 11(b) shows the result of the NIR scan over the area enclosed by the dotted lines. It can be seen that through-transmission amplitudes are reduced in the region of the delamination. A similar scan is shown in Figure 11(c,d) for an enlarged area of delamination, which is evident by inspection of the resulting NIR through-transmission image. Note that the NIR measurement also appears to be detecting structure within the sample which is also likely to have resulted from the manual mechanical delamination process, and which is not visible by eye.
Figure 11: (a) Photograph of the top surface of the GRP sample, with the extent of delamination shown by the thin solid black line. The approx. area covered by the NIR scan is denoted by the dotted lines. (b) The resultant NIR scan. (c) and (d): As Figure 10, but now for a delamination that has reached both further into and across the sample.

C. Use of NIR spectra to detect water in solar panels

As stated above, water has a distinctive NIR spectrum. Hence, it was thought interesting to use an alternative arrangement to the spectral measurement system of Figure 3 so that measurements could be performed in reflection. The particular NDE problem under investigation was the detection of water ingress into solar panels. While camera-based thermography has been applied to detecting faults and operational problems in photovoltaic solar panels [19], water ingress is a particular problem that is of interest to the power generation industry.

The experimental arrangement used to investigate this problem is shown in Figure 12. The same mid-IR halogen source and photodiode detector as described earlier were used in reflection mode, and the whole system could be scanned over the solar panel surface as shown in the figure using a PC-controlled X-Y stage. Experimentally, the received spectrum was recorded at each individual point over the scan area, at intervals of 1 mm. Note that a typical solar cell contains a polysilicon semiconductor substrate together with an upper glass protection layer. It is the presence of water between these two layers that is of interest.
The spectra that were recorded under specific conditions are shown in Figure 13. The spectrum for bare silicon is essentially flat over the 800 – 2000 nm range, and does not show any appreciable features when the glass cover is present. However, when water is introduced between the two, the characteristic double absorption peaks seen earlier in Figure 7 are evident as a reduction in intensity.

Maps of the total reflected intensity across the 1000-2000 nm spectral range were recorded over an area of panel partially containing water, and the recorded intensity represented as a colour map as shown in Figure 14. The dotted line indicates the region within which water was located. Also shown are spectra at two specific locations, one wet and the other dry. As can be seen the data shows a clear indication of the presence of water, with the expected variation in spectral content at the pixels identified by the black arrows.
Figure 14: Colour plot of an 8 mm x 12 mm area of a solar panel structure which was known to contain water in the region above the dotted black line. Spectra are also shown for two specific regions – one wet and the other dry.

Based on this information, it is possible use filters to plot images that would be obtained at certain narrow frequency ranges, in particular across that that contain the two main absorption bands of water. The results are shown in Figure 15. It can be seen that excellent results could be obtained by concentrating the measurement on either absorption band wavelengths, but as expected, more contrast occurred for the stronger band over the $\lambda = 1900 – 1950$ nm wavelength range. This means that discrete, more powerful sources (such as laser diodes) could be chosen in a practical NDE application, one example being the use of drones for the rapid inspection of solar panel arrays.

Figure 15: The image shown in Figure 14, but filtered over the two specific wavelength ranges indicated.
Conclusions

It has been shown that near infrared NDE has some promising applications. It can be used to inspect composite materials where other techniques (such as ultrasound) may have difficulty due to scattering, small sample thickness etc. Moreover, it is total non-contact, and lends itself to rapid scanning and large area inspection. It is thought to be particularly promising for the inspection of composites during manufacture, but could also be applied to areas such as solar panel inspection in large installations.

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