OPTICAL FIBRES FOR IN SITU MONITORING THE DAMAGE DEVELOPMENT IN COMPOSITES AND THE RELATION WITH ACOUSTIC EMISSION MEASUREMENTS

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ABSTRACT

The complex damage development process in composite materials demands a system that could continuously monitor their damage state in particular structural applications. Fibre optic sensors embedded in the composite material could offer an alternative for the robust piezoelectric transducers used for acoustic emission (AE) monitoring. For simplicity and robustness reasons, intensity-modulated optical fibres were chosen to detect damage in CFRP composite laminates based on the microbending concept. Advanced signal processing techniques based on time-frequency analysis have been applied on the signals collected during loading of the CFRP composites. The short-time Fourier transform has been computed and noise reduction algorithms (adaptive filtering and spectral subtraction filtering) have also been used. The transient signals being detected can be correlated with AE signals, analysed with a modal AE system. The signals are attributed to the initiation of damage in the materials and thus the optical signal contains, besides the level of overall strain, information in the elastic energy released whenever damage is introduced in the host composite.

INTRODUCTION

The emergence of optical fibre communication technologies in the 1970’s has enabled the development of embedded optical sensors for process condition monitoring and for smart materials/structures applications (1,2). We also initiated a study to incorporate optical fibres in carbon-fibre reinforced epoxy laminates in order to monitor the fatigue behaviour characterised by a gradual damage development. The method of embedding the optical fibres and their influence on the mechanical behaviour of the host material has already been evaluated for a number of laminates and the embedding positions have been optimised (3,4,5).

The present paper is focused on the signal processing of the optical fibre data, done in collaboration with the Department of Electrical Engineering. The signal processing has been done in order to find a relation with the internal strains in the composite produced on one hand by the external loading (stresses and temperature) and on the other hand by the internal damage development. Especially for the latter an attempt will be made to correlate the signals measured with the AE technique, in which we already have proven its competitiveness more than once (6,7) and the signals of the embedded optical fibres. With optical fibres embedded in composite materials and intelligent data processing of the optical fibre signals, one can integrate a NDT-system into this complex material, or derived component or structure, similar to the neural system in a human body.

The fibre optic sensors have several advantages compared to the electronically based sensors like piezo-ceramics such as light-weight, all passive configurations, low power utilisation, immunity to electromagnetic interference, high sensibility and bandwidth, compatibility with optical data transmission and processing, long lifetimes and low cost (as long as using silicon fibres). Disadvantages exist with reparability as long as optical
fibres have to be integrated into the material and placed according to major occurring stresses and strains to obtain reliable data.

**PRINCIPLE OF OPERATION**

To detect damage, two kinds of optical sensors can be used: phase-modulated sensors (interferometers) and intensity-modulated sensors. The former is usually more sensitive but also very fragile. A sensing system, which is simple and robust enough for industrial use, is offered by intensity-modulated optical sensors. The intensity variations of the transmitted light are caused by a perturbing environment. If for instance the optical fibre is bent, small amounts of light are lost through the cladding because the condition of total reflection is violated. The amount of intensity loss depends on the amount of bending. The stress field in a composite material is influenced by the external loading and the internal damage in the material. This may cause the optical fibre to bend in the material so that a decrease in intensity of the transmitted light can be seen. Initiating and growing damage is associated with acoustic stress waves propagating in the material. When a wave encounters an optical fibre, this bends locally and so some light might also be lost. A high sampling rate (SR) can be used to detect those transient signals released by matrix cracking, delamination or fibre fracture phenomena. To reveal this information from the optical signals, signal analysis tools such as filtering, time analysis and time-frequency analysis is required.

**EXPERIMENTS**

Our previous study addressed the choice of fibres, the embedding procedure and the influence of the optical fibres on the mechanical properties (monotonic tension, three and four point bending and tension fatigue) of different carbon-epoxy composite laminates. The next step was to evaluate the performance of the optical fibre NDT system.

*Fig. 1: The sensing system*

1 : Laser source  
2 : Optical coupler  
3 : Optical fiber  
4 : Composite specimen  
5 : Photodiode + amplifier  
6 : Computer (oscilloscope card)  
7 : Workstation  
8 : AE sensor

Laminates were produced from a Vicotex 6376/35/137/T400 C/epoxy prepreg. The prepreg was cut and stacked into a $(0^\circ, 90_4^\circ)$, lay-up. The optical fibre was embedded in the $90^\circ$ direction in the middle plane of
the specimen. A polymeric bore tube was put around the optical fibre at its exit point from the composite specimen. It shrank around the fibre during the cure and so protected this weak point. The samples tested had the following dimensions: 150 mm length, 25 mm width and 1.2 mm thickness.

A He-Ne laser source was used to power the multi-mode optical fibre embedded in the carbon-fibre reinforced composite material. The output light intensity was collected by a photo-diode, and was sent to a computer via an oscilloscope card as seen in Fig. 1 of the sensing system.

The optical signal post-processing was done on a SUN workstation using MATLAB® software, in particular the signal processing toolbox. A program was written to filter the signal, to compute its STFT and to visualise the changes in its power spectrum over time (9). Additional tools were developed to extract damage related information from this time-frequency analysis.

An acoustic emission (AE) system was also used to monitor the damage development in this composite laminate: the Wave Explorer from Digital Wave Corp. This system is equipped with broadband sensors (Digital Wave B1025) with a nearly flat frequency response in the 50–3000 kHz frequency range. It uses the plate wave theory as a theoretical background and analyses the waves according to their mechanical nature, namely, extensional and flexural waves. It is called a modal AE (MAE) system (10,11). MAE allows a more convenient way to identify the kind of damage by looking at the frequency content of the acoustic waves produced. The presence (or absence) of extensional and flexural modes is the key to the damage mode characterisation. It has been proven to work in an efficient way for matrix cracking and fibre fracture (12). It also allows a clear recognition of noise grip and EMI.

On the oscilloscope card, three channels were used. One channel was used to collect the optical signal, another channel collected the optical signal filtered using a capacitor to get only the ac component amplified 11.5 times, and a third one to collect a trigger signal sent by the AE system each time an AE event is detected. The sampling rate (SR) was set to 10 kHz.

Tensile tests were performed on Instron 4505 universal testing machine with a 100 kN load cell. To prevent grip failure, aluminium end tabs were bonded to the specimens using a two-components Araldite 2011 epoxy glue. The displacement rate was 0.5 mm/min and a Labview program drove the tensile machine and the oscilloscope card.

RESULTS AND DISCUSSION

Ten specimens were tested and at the beginning of each tensile test, pencil-lead break tests were performed for calibration purpose.

Low pass filtering

The tensile load curve of one test is shown in Fig. 2. During the first 90 s, several pencil-lead break tests were performed to calibrate the AE system. Then, the loading was applied until the final fracture. After 261 s of test, there was a sudden decrease in the applied strain due to some damage near one of the aluminium tabs. Figure 3 shows the optical signal for the same test. A 4th-order low pass (LP) Butterworth filter was applied with a 5 Hz cut-off frequency. The curve has been reversed for better comparison with the preceding one. The optical
intensity starts to decrease when the loading starts to be applied. A low-frequency oscillation can be seen on the curve and is due to vibrations produced by the Instron machine. The final fracture is clearly seen and the strain release at 261 s also appears as a change of slope on the curve. It is thus shown that the optical signal contains information on the strain produced by external loading.

![Fig. 2: The loading versus time curve.](image1)

![Fig. 3: The optical signal filtered with a low pass Butterworth filter.](image2)

Some sharp spikes are also hidden in the curve of Fig. 3. To see them more clearly, the same low pass filter was applied to the ac component of the optical signal (amplified 11.5 times). As can be seen on Fig. 4 the signal is constant except for some big spikes. The time instant at which those spikes appear is the same as the time of occurrence of some AE events. These AE events can be related to damage inside the material, so those spikes can also be related with the damage, which causes a sudden strain energy release in the material. By removing the 5 digits offset and taking the absolute value of this signal, a threshold can be set and damage detection is achieved.

![Fig. 4: The ac component of optical signal filtered with a low pass Butterworth filter.](image3)
The main limitation is the sensitivity; the events detected by this method are only the most energetic ones. The less energetic events detected by AE cannot be seen on the optical signal or are smaller than the curve oscillations and can therefore not be detected by the threshold technique. Removing the polyimide coating from the optical fibre may increase the system sensitivity.

Most of the high-frequency components are filtered out with this low-pass filtering technique so the signal cannot be used for damage identification. Another drawback is that changes are less sharp and some delay may also appear. This method shows that damage detection is possible with intensity modulated optical sensors based on the microbending concept, but some more advanced signal analysis techniques are required to have information on the kind of damage so this low-pass filtering has to be replaced.

**Noise reduction**

If one has to look for small effects on the optical signal the Signal to Noise Ratio (SNR) has to be increased. The biggest noise source is from the laser power supply (50 Hz and the harmonics from the net). An *adaptive filter* was used to remove this noise only up to 1 kHz (13) because this filter was computation time consuming. Subsequently, *spectral subtraction*, a filtering technique used in speech processing (14), was applied to see more clearly the expected ‘optical events’. This technique requires that the background noise environment remains locally stationary to the degree that its expected spectral magnitude value just prior to an expected event equals its expected value during the event. It is also assumed that significant noise reduction is possible by removing the effect of noise from the magnitude spectrum only.

These techniques were applied to pencil lead break tests (Fig. 5) and on optical signals from real damage (as indicated by AE) during tensile tests (Fig. 6). They allow a good noise reduction without reshaping too much the signal.

![Fig. 5: The original optical signal, the signal filtered with an adaptive filter and with the spectral subtraction method of a pencil lead break.](image-url)
Fig. 6: The original optical signal, the signal filtered with an adaptive filter and with the spectral subtraction method of a real damage event.
Time-frequency analysis: STFT

Since the expected signals were non-stationary (transient), their frequency content, visualised by the Fourier transform, varied in time. The short-time Fourier transform (STFT) can be used to visualise the frequency content of a signal over time (13). This so-called spectrogram is visualised in Fig. 7 (middle) for the 400–3500 Hz frequency range. This figure corresponds to the specimen final fracture event that can be seen in the time domain in the top curve. For better view and analysis, the frequency projection of the spectrogram can be computed (see bottom).

Damage identification

The filtered optical signal corresponding to a pencil lead break was extracted and a time-frequency analysis (STFT) was performed. Both the AE time signal and the optical time signal (respectively seen in Figs. 8 and 9) show a small extensional component followed by a big flexural mode. This is coherent with what can be expected from a pencil lead break test done on the surface of the specimen. Waves produced by a pencil-lead break test are quite similar to those produced when damage occurs in a composite material.
Figures 10 and 11 show the ac optical signals corresponding to AE events recorded during the tensile test (middle and bottom). The time-frequency analysis clearly identifies special features in the signals, which can be attributed to matrix cracking or fibre fractures based on their time of occurrence.

Fig. 10: The ac optical signal, the filtered signals (adaptive filter and spectral subtraction method) and the frequency spectrogram of an AE event detected in the middle of the tensile test.
CONCLUSION

It has been shown that an intensity modulated optical sensor based on the microbending concept can be used for continuous damage monitoring of a carbon-fibre reinforced laminate composite. The NDT system is simple and robust, but requires some advanced signal analysis tools like adaptive filtering, spectral subtraction filtering, and time-frequency analysis (STFT).

The intensity-modulated optical fibre sensor (microbending principle) can detect pencil-lead breaks, the overall strain in the composite and strain variations due to damage development during loading. The similarities between optical and MAE signals should permit damage identification. The damage location has not been studied so far, this may require to embed several optical fibres in the specimen.

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REFERENCES

2. N.D. GLOSSOP and al., Optical fibre damage detection for an aircraft composite leading edge, Composites, 21, (1990), 71-80.