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Review

Review of structural health and cure monitoring techniques for large wind turbine blades

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A review of structural health monitoring methods, including residual cure strain monitoring is presented for the wind turbine blade industry. A comparison is presented for dielectric, acoustic, ultrasonic, thermal and fibre optic monitoring methods. This review highlights the need for further development in this area, with potential savings to manufacturing time and reductions in cost through quality control measures, including furthering the scientific understanding of cure strain, are just some of the downstream benefits. Upstream benefits include increased investor confidence through better design, manufacture and operational practises.

1. Introduction and aims of SHM

Structural health monitoring (SHM) typically utilises sensors to give continuous online feedback of the component's structural integrity. SHM is now an independent multi-disciplinary area of research dedicated the development of smart or intelligent materials and structures, primarily used in civil and aerospace applications [1]. Smart materials with SHM are likened to the human body's nervous system (Fig. 1), with sensors analogous to nerve endings able to detect damage or pain. The central processing unit (CPU) is compared to the brain, able to interpret the incoming signals and react with an appropriate response. This response would usually involve energising actuators or muscles to shift the component or limb out of danger wherever possible.

Although the active sensor feedback is the ultimate aim of SHM, it is rarely realised in practise due to the difficulties creating a robust CPU able to interpret incoming signals and react correctly in all situations. Typically the feedback from sensors is relayed to a human operator who is then trained to take the necessary action. Any feedback is generally limited to an emergency shut down once a limit state is reached.

SHM use in wind turbine rotor blade (WTRB) applications is currently limited to experimental prototypes such as the Enercon 4.5 MW, retro fitted with a fibre optic FBG sensor array [2]. However, robust industrial systems are now increasingly being deployed, such as the Moog Insensys fibre optic sensor array specifically designed for WTRB applications [3]. The SHM of WTRB is typically limited in active feedback, with sensors typically utilised for the following purposes:

- Safety monitoring and active safety control of the blades [2].
- Accumulating strain load data for future design calculations [2].
- Accumulating load data for future wind park site characterisation [2].
- Accumulating strain load at differing blade locations for future blade design optimisation [2].
- To predict consumed and residual lifetime, forecasting product replacement and maintenance requirements in an effort to reduce down time [3].
- "Black box" technology providing detailed load data in the event of an overload failure [3].
- Ice load monitoring [3].

SHM of WTRB is currently utilised to collect strain load data which can be used to increase the understanding of operational load regimes [2]. In conjunction with accurately designed and produced WTRB, SHM technology is also capable of detecting critical load conditions and predicting maintenance schedules [3]. As the cost of SHM reduces and WTRB sizes increases it is likely that the majority of large scale off shore turbines will incorporate SHM.

Future SHM systems have the potential to reduce loads with the use of active feedback and individual blade pitch control [3]. As

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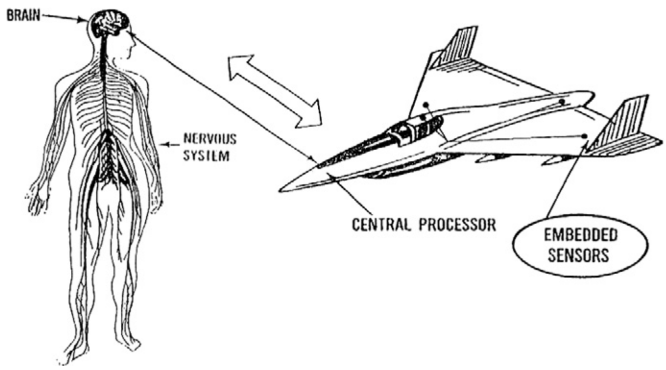

Fig. 1. Analogy of SHM with the human nervous system [1].

rotor sizes increase the wind speed is less likely to be uniformly distributed throughout the swept area [3]. Therefore, the use of individual blade pitching regulated by sensor feedback could facilitate increased turbine output through optimised control. Individual pitch control (APC) has been shown to reduce blade loading and is currently being implemented in next generation turbine designs. To enable APC to be implemented, a fibre optic load measurement system is incorporated in the blade during construction to provide load information to the turbine control system.

1.1. Practical SHM systems for wind turbine blades

In order to capitalise on the benefits of structural health monitoring (SHM), a system capable of continuous online monitoring is required. Numerous inspection methods exist for composite materials, capable of detecting damage and deformation [1,4]. The majority of inspection techniques are only suitable for post-production inspection prior to blade fitting. A limited number of inspection methods can be applied to a stationary fitted blade. In practise, Acoustic emission monitoring (Section 1.2) and strain monitoring (Section 1.3) are the only currently available methods offering potential for continuous online monitoring for WTRB.

1.2. Acoustic emission monitoring

The Acoustic emission (AE) phenomenon is based on the release of energy in the form of transitory elastic waves within a material having a dynamic deformation process [1]. Typically sources of acoustic emission within a material are:

- Crack initiation and propagation [1].
- Breaking of fibres.
- Matrix cracking and fretting between surfaces at de-bonds or de-laminations.

Therefore, AE techniques offer the possibility of detecting the real time existence of evolutionary defects, where passive defects are not detected [1]. AE monitoring utilises surface mounted piezoelectric sensors to detect the elastic stress waves within the structure. The system is very sensitive and can detect much weaker signals than normally audible [5]. Detection of an acoustic emission is known as an event, events trigger electrical signals from the sensors. If the signal exceeds the users predetermined threshold then the event is logged. A logged AE event is known as an AE hit. Hits are characterised by amplitude, energy, counts, duration, rise time, counts to peak and average signal level. The location of AE events can also be found by zone location, the event is registered by a single sensor, determining its locality to the sensor. AE events can also be located using triangulation methods, calculating its position relative to three sensors with known times of signal arrival [5].

AE monitoring has yet to be successfully applied in the continuous operational monitoring of WTRB. A high level of background noise is found during turbine operation. Therefore, difficulty in extracting a useful signal is predicted. Experimental applications of AE in operational online monitoring of WTRB have shown high AE emissions in healthy blades without explanation [6]. AE monitoring is successfully applied during the static and fatigue testing of WTRB (Fig. 2) [5,7]. In service AE monitoring can be conducted on stationary blades (Fig. 3) [6]. Results from AE analysis show increased hits around the failure site and also record hits in other areas suspected to be possible secondary failure sites (Fig. 4) [7]. AE sensing requires electronics in the blade which are prone to lightning strikes. They also require a complex sensor network in the blade and are hence unlikely to be used in operational machines.

AE monitoring has the ability to identify damage and its location when the blade is stationary. However, AE monitoring has yet to be perfected for operational in service monitoring. AE monitoring has the advantage of monitoring the entire blade with relatively few sensors. However, its use in blade failure and service predictions requires significant calibration. The calibration in the level of AE emissions which results in failure or required service is required and likely to differ with each blade design. Load conditions below the threshold of damage propagation remain unrecorded as AE emission monitoring registers only progressive defects. Therefore, its use in active control and continuous load monitoring is limited.

1.3. Strain monitoring

Strain monitoring is the detection of microscopic changes in length in a component at pre-selected points, and does not directly detect damage in a structure. Changes in length or deformations can be related to material stress and load (Section 1). Total deformations of large components such as WTRB can be large (up to 9 m tip deflection in a 60 m blade), which can be visually detected. This deformation is a sum of all local deflections. Therefore, total deformation gives no indication that any material has reached its

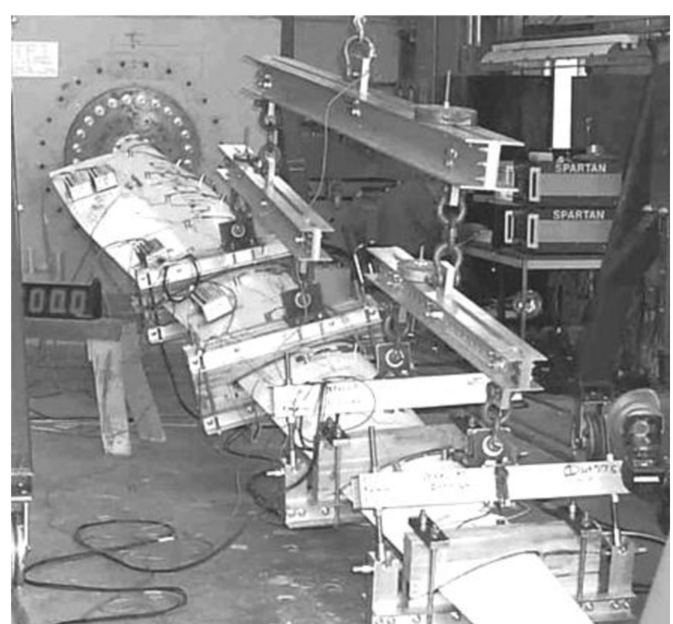

Fig. 2. AE monitoring of a wind turbine blade during static testing [7].

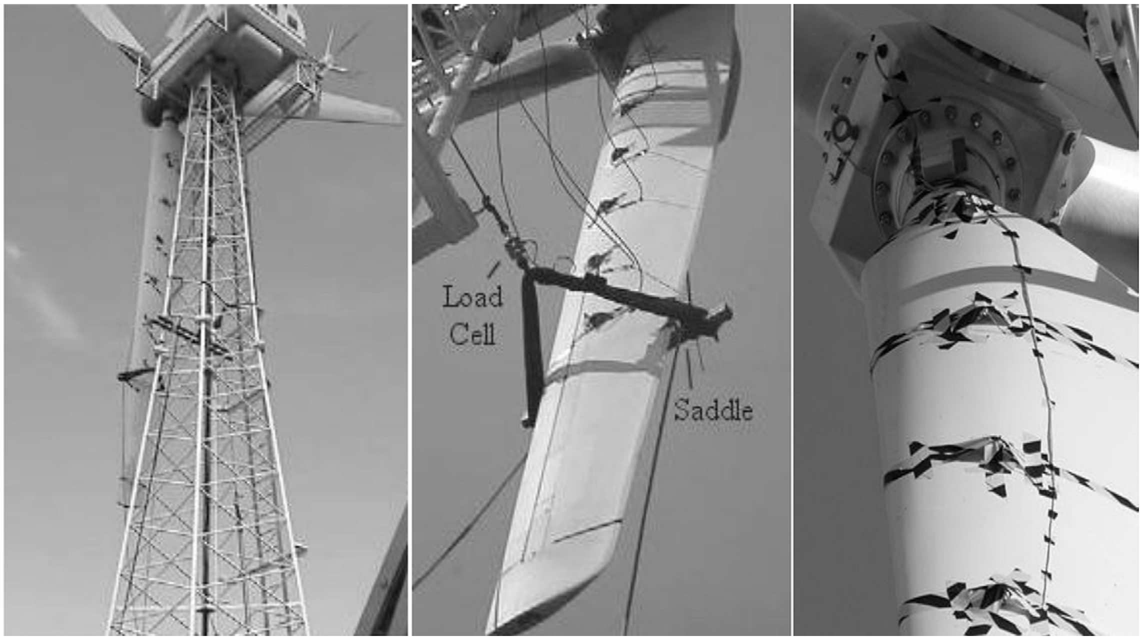

Fig. 3. AE monitoring of a stationary WTRB in service [6].

limit at a local position. For information on material strain levels at a local level, strain sensors must be utilised (Section 1.3.2) which detect minute changes in length. However, such microscopic sensors measure only point strain thus limiting their applicability in overall component damage sensing applications. Prior knowledge of strain and stress distributions and possible critical points are necessary, even a dense array of sensors could be insufficient [1].

Strain sensing can be utilised for continual in service operational monitoring and has been successfully utilised in a 4.5 MW turbine providing two years of continuous operational blade load data

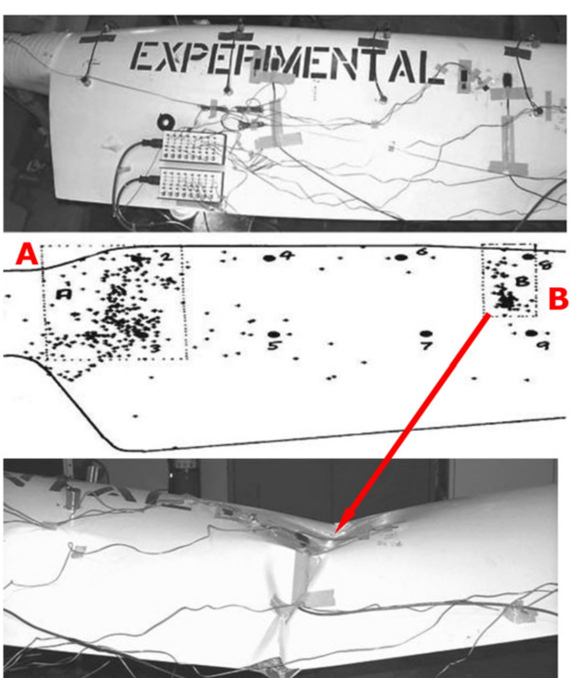

Fig. 4. The failure site registered by AE monitoring (B) with possible secondary failure site (A) identified [7].

using optical fibre Bragg grating (FBG) sensors (Fig. 5) [2]. However, to predict blade failure, prior knowledge of the WTRB component's stress field is required so that sensors can be mounted in critical areas. Characterisation of the strain level which results in blade failure will also be required to accurately set a limit state. Despite difficulties FBG strain sensing has the potential to realise all the benefits of SHM.

1.3.1. Basic strain theory

All structures are made from materials that deform under applied loads, these deformations are characterised as the dimensionless quantity known as strain [8]. Two types of strain are defined dependant on loading conditions, these are direct strain (found in the spar cap component of WTRB) and shear strain (found in the shear web component of WTRB). Direct strain is a result of directly opposing forces developing compressive or tensile load conditions resulting in a change in length of the material (Equation (1)) (Fig. 6). Shear strain is a result of offset forces developing a shear load condition resulting in an angular deformation within the material (Equation (2)) (Fig. 7).

Definition of direct strain [9]

$$\text{direct strain} = \frac{\text{change in length}}{\text{original length}} \quad \varepsilon = \frac{x}{l} \tag{1}$$

Definition of shear strain [9]

$$\text{shear strain} = \frac{\text{deformation}}{\text{original dimension}} \quad \gamma = \frac{x}{l} \tag{2}$$

Hooke's law states that within the elastic range for any given material, the deformation is proportional to the applied force producing it [9]. Therefore, within the elastic range of a material, stress is proportional to strain (Equation (3) and (4)). The shear and stiffness modulus and maximum allowable stress can be characterised for a particular material experimentally (Table 1), although with more difficulty for non-isotropic WTRB composite materials [10]. Therefore, by measuring the strain in a material with known characteristics the stress and therefore forces can be calculated

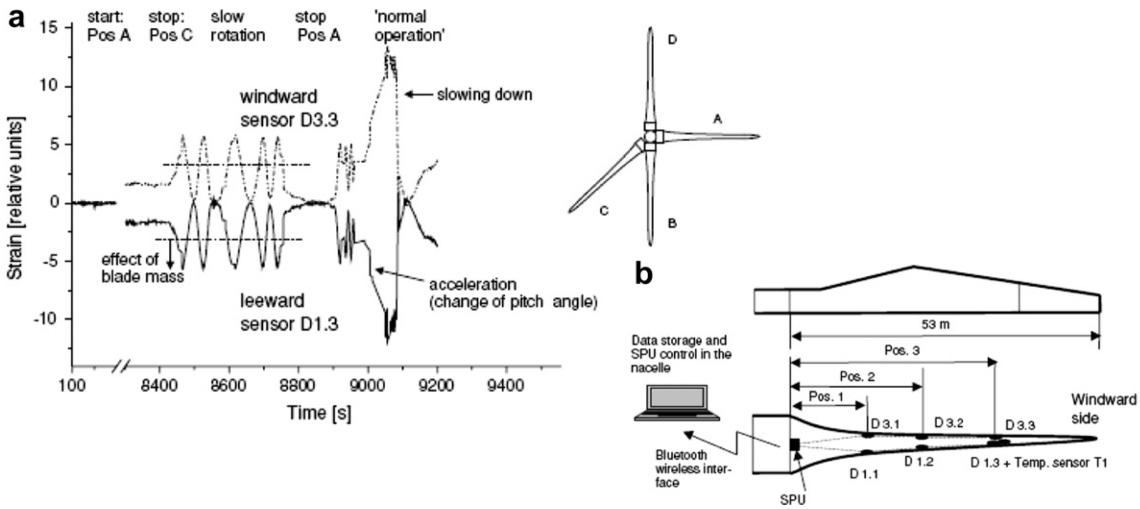

Fig. 5. FBG sensor positions and measured strain in a WTRB [2].

provided the exact dimensions are known. Additionally, if the maximum allowable stress of the material is known then failure can be predicted reasonably accurately.

Modulus of elasticity

$$\text{constant} = \frac{\text{direct stress}}{\text{direct strain}} \quad \text{stiffness modulus } E = \frac{\sigma}{\varepsilon} \tag{3}$$

Modulus of rigidity

$$\text{constant} = \frac{\text{shear stress}}{\text{shear strain}} \quad \text{shear modulus } G = \frac{\tau}{\gamma} \tag{4}$$

1.3.2. *Sensor types*

Two popular sensor groups exist for the purpose of strain measurement, traditional electrical and relatively modern fibre optic. Electrical strain gauges have become so widely accepted that they dominate the entire strain gauge field except for special applications. With electrical resistance the most important and popular type [4]. However, recent advances in fibre optic FBG sensors have led to a rise in their popularity especially within WTRB [11].

1.3.2.1. Electrical sensor types. Several electrical sensor types exist including capacitance, inductance, semiconductor and resistance. Each is sensitive to a differing electrical property. Capacitance, inductance and semiconductor types are utilised less frequently with resistance types the most popular, described as a mature measuring system [4].

Capacitance sensors operate on the principle of measuring capacitance change within a sensor firmly secured to the component. Three mechanisms can lead to a change in capacitance which is proportional to displacement [4]:

- Changing the gap between capacitor plates.
- Moving plates creating an offset, reducing the capacitance area.
- Introducing a body with a dielectric constant higher than air within the gap.

Capacitance sensors are considered inferior to resistance gauges due to their relatively large size and knife edge mechanical attachment. However, capacitance sensors offer greater stability in higher temperatures as the dielectric constant of air changes little up to 815 °C [4].

Inductance sensors operate on the principle that changes in the position of the core within a wire coil can generate a proportional voltage change. Inductance sensors offer no advantage over resistance gauges, are relatively large and suffer from attachment problems. Therefore, they are rarely used within specimens. However, their typical application is in the use of extensometers used in the tensile testing of materials to determine their stress-strain response [4].

Semiconductor sensors operate by recording the changes in piezoresistance in semiconductor materials. The sensors offer the advantage of small size and high sensitivity and thus can be utilised where little deflection is recorded. However, they are rarely utilised in practise due to high cost, limited range and large temperature effects [4].

Resistance strain gauges operate by recording the change in resistance of an electrically conductive wire relative to displacement. The change in resistance is a result of change in cross sectional area and length of the wire as the specimen is elongated. Resistance strain gauges are the most popular method of strain measurement. Many sizes and types are available (Fig. 8). Typically

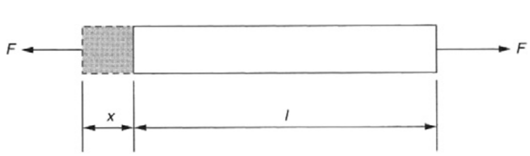

Fig. 6. A direct strain load condition resulting in displacement (x) [9].

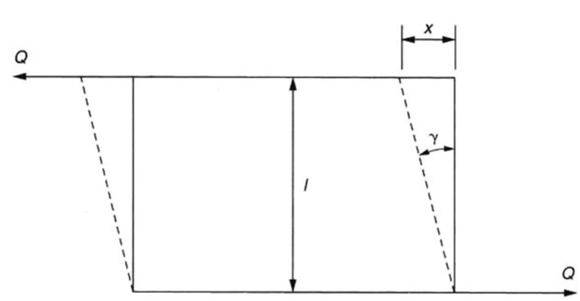

Fig. 7. A shear strain load condition resulting in deformation (x) [9].

Table 1
Modulus of elasticity and rigidity for typical isotropic materials [9].

Material	Modulus of elasticity (E) GN/m^2	Modulus of rigidity (E) GN/m^2
Mild Steel	212	82
Aluminium	70	26
Titanium	116	44

three sensors are integrated to form a rosette which is capable of measuring strain and determining principal directions. Typically the strain gauge is bonded to the surface of a component (Fig. 9). A Wheatstone bridge circuit is used to measure resistance changes accurately.

Typically low cost foil strain gauges are used, which are small precision resistors mounted on a carrier that is bonded to the component part (Fig. 9). Therefore, results obtained are a function of installation procedure, state of the strain being measured and the environmental conditions during the test. The typical accuracy of ($\pm$0.5%) can be compromised [4]. Strain gauges can suffer from non-linearity, hysteresis and zero shift due to cold work of the foil material, poor bond and viscoelastic effects of the carrier material [4]. Strain gauges are also susceptible to changes in temperature which must be carefully compensated for in the results [4].

Electrical strain sensing is a well-established mature technology with a range of low cost equipment and sensors available. The equipment, when correctly installed, has the ability to produce accurate results. However, electrical sensors suffer from several disadvantages when utilised in composites and within WTRB applications:

- An indirect measurement of strain.
- Limited to surface strain measurement.
- Sensor size results in abnormal strain conditions when embedded within a composite.
- Susceptible to lightning strike and electro-magnetic interference.
- Degradation occurs over long term fatigue loading conditions [4].
- Requires multiple copper wire connections.

1.3.2.2. Fibre optic sensor types. The growth of fibre optics within the telecommunications industry has made fibre optic equipment

Fig. 8. A variety of low cost foil strain gauges [www.hbm.com].

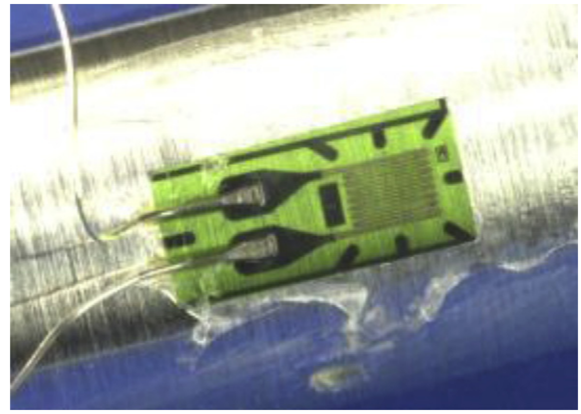

Fig. 9. A low cost foil sensor bonded to a test specimen [www.prosig.com].

commercially available at competitive costs. Therefore, the fibre optic (FO) sensor community has benefited from this availability and economic effect, as many new fibre sensor architectures and deployment applications of fibre sensors have been demonstrated [12]. Typically three techniques have been utilised in fibre optic sensing; intensity based, phase modulated interferometers and wavelength based sensors.

Intensity based fibre optic (IBFO) sensors are the simplest and were therefore the first FO devices to be utilised. An IBFO proximity device measures the intensity of light returning to the fibre after reflecting a small distance over an opening where the intensity of the light reflected is proportional to the displacement.

Alternatively, losses in an FO cable can be seen to increase with micro bending of the fibre. Micro bending losses can be measured in a fibre which has been positioned to bend during displacement, where the losses are proportional to the displacement.

Additionally, the light reflected at the tip of a fibre is, according to Fresnel Law, proportional to the refractive index of the surrounding media [1]. The refractive index of resin is known to change with the extent of cure, therefore this phenomenon has been used for cure monitoring [1].

IBFO methods are used commercially in proximity sensing and experimentally in cure monitoring. However, micro bending sensors have been typically abandoned due to fluctuations in optical power at the light source, connectors, temperature etc. which made the system inaccurate [1].

Phase modulated optical fibre sensors, or interferometers operate on the principle that reflected monochromatic light will interfere with the original light source causing measurable light and dark fringes dependant on deflection. An accuracy of 10 nm can be detected, making it the most accurate laboratory technique for precise distance measurement [1]. Several sensor architectures exist, with the commercially available Fabry-perot system most common. Extrinsic Fabry-perot heads, known as micro cavities have a precision machined wafer bonded to the end of the optical fibre leaving a small air gap creating miniature pressure and temperature sensors [1]. Typically these sensor types are less favoured as they allow only a single sensor per fibre, thereby excluding multiplexing.

Wavelength based sensors, or Fibre Bragg Gratings (FBG) have been the main focus of attention since their discovery at the beginning of the 1990s [1]. The FBG sensor operates on the principle of detecting a narrowband of reflected light whose frequency changes relative to deflection. The core is engraved for a short length (approx 10 mm) with a periodic modulation of its refractive index, which behaves as a series of weak partially reflective mirrors (Fig. 10). By an accumulative phenomenon known as diffraction, the

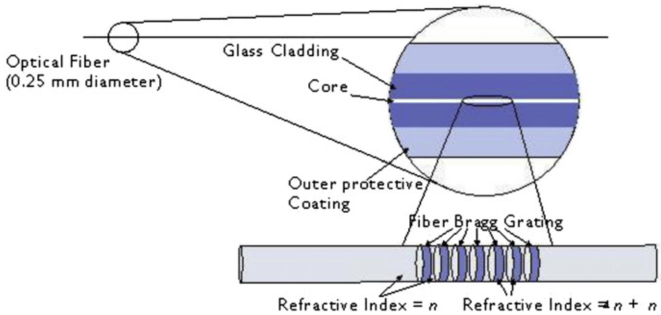

Fig. 10. Structure of the fibre Bragg grating (FBG) sensor core [3].

optical wavelength that is exactly proportional to their spacing is reflected back. Therefore, the Bragg grating behaves as a very narrow-bandwidth optical filter. If the grating is subjected to a uniform axial strain, or a uniform thermal increment is applied, the wavelength of the spectrum reflected by the grating will shift as a result of changes in the pitch and refractive index [1].

The ability to engrave several sensors on a single fibre, known as multiplexing, is a distinct advantage. Two methods of multiplexing are possible where sensors are discriminated by either the wavelength reflected, known as wavelength division multiplexing (WDM) or the time taken for the reflected signal to return, known as time division multiplexing (TDM) [13]. WDM requires all the sensors on a single fibre to have a different Bragg grating spacing, therefore reflecting differing wavelengths (Fig. 11). Excessive deflections may lead to errors using this method as one sensor may enter the wavelength zone of another, therefore to allow sufficient sensor range the number of sensors may be limited (a maximum of 4 sensors based on a 40 nm scanning etalon filter with sensor ranges of 8.9 nm [11]). In TDM, a recent development [11], all FBG sensors are written at the same wavelength. An interrogation unit receives a number of pulses which arrive at a time determined by the grating distance. This indicates that a certain distance is required between each sensor (usually 100 m) and therefore the allowable number of sensors is typically limited by FO losses (typically 100 sensors are possible per fibre [11]). WDM requirement for an expensive tuneable laser filter coupled with the cost of writing differing gratings indicates that TDM sensor interrogation is now preferred [11].

FBG sensors are sensitive to the effects of temperature as a result of the linear thermal expansion of the grating and changes in its refractive index. Equations are available which characterise these temperature effects [1] where the change in refractive index is the dominant factor. For accurate strain measurement, temperature effects need to be corrected, in the same way as common strain gauges.

Generally FBG sensors have the following advantages:

- Offer a direct physical correlation between wavelength and strain [2].
- No recalibration of sensors required, even after the signal processing unit has been exchanged [2].
- Long signal transmission lines with very low or negligible losses [3].
- Multiple sensors (up to 100) on a single transmission line [3].
- Long term stability under operation in hostile environments [3].

For WTRB applications, the use of FBG sensors has proven feasible and reliable for a period of two years within a 4.5 MW large scale wind turbine [2]. FBG sensors offer a practical solution to SHM within WTRB due to favourable characteristics:

- *Sensor size*, The minute size allows FBG sensors to be embedded directly within the composite material without creating voids or stress raisers (Fig. 12) [3].
- *Non electrically conducting transmission lines* ensure lightening safety and neutrality to electro-magnetic interference [2].

2. In-situ cure monitoring

2.1. Introduction

Typically, monitoring the cure process within the WTRB industry is limited to time and temperature. A cure schedule is carried out as recommended by the resin manufacturer. Therefore, a system of cure monitoring would offer advantages in [14]:

- Allowing tailored cure schedules to suit the resins age and chemical integrity.
- Measuring residual stresses.
- Indicating when cure is complete.
- Assisting in maintaining product quality, repeatability and reducing scrap rates by offering quantitative feedback on the cure process.

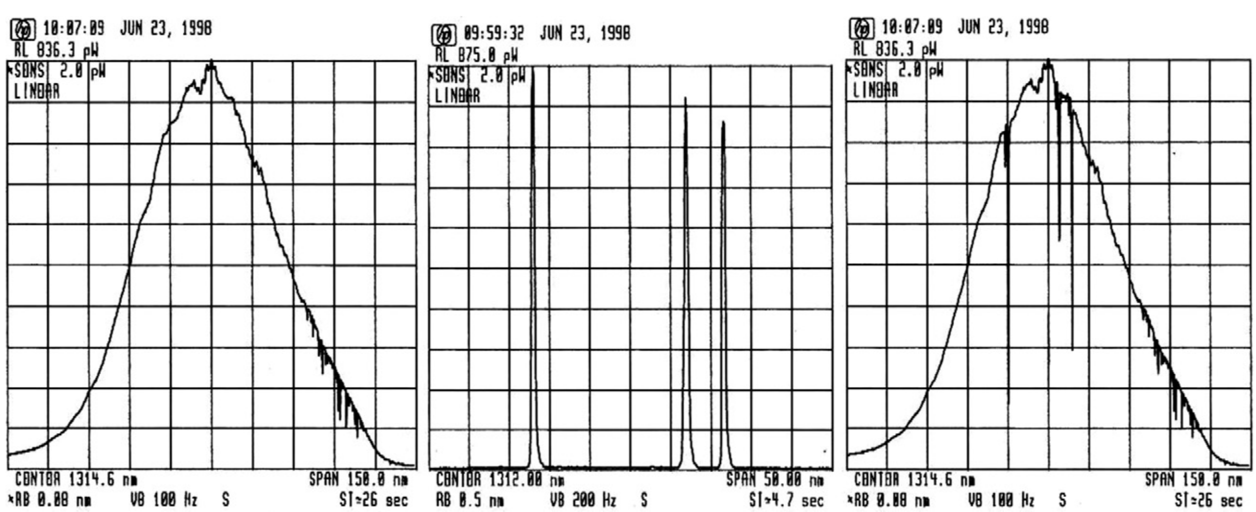

Fig. 11. The broadband spectrum input (left), reflected signal (centre) and transmitted signal (right) of three wavelength multiplexed FBG sensors [1].

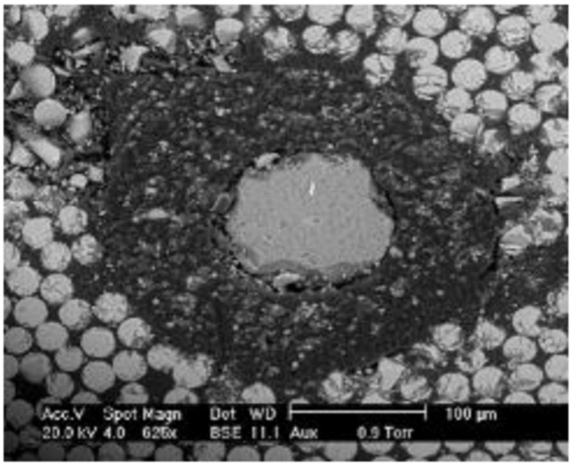

Fig. 12. An embedded fibre optic sensor.

Prepreg material is pre catalysed and begins to cure the moment its leaves the resin manufacturer. Therefore, prepreg is freezer stored to slow the curing process dictating a limited shelf life. The chemical integrity of the prepreg resin is dependent upon the time of usage and process variables in prepreg manufacturing. Therefore, an individually optimised cure schedule is desirable [14].

WTRB composites are processed at high temperatures, therefore when the mould is cooled the differing thermal expansion of the matrix and reinforcement dictate that residual stresses will be present in the finished component. Resin shrinkage during the cross linking polymerisation process contributes to the residual stresses. Residual stresses can introduce damage in the form of matrix cracks and delamination resulting in significant warping of the finished component. Therefore, careful cure monitoring could assist in perfecting the process and reducing residual strain [14].

A reduction in cycle time and energy costs may be achieved using cure monitoring. Direct determination of when cure is complete will allow the heat source to be terminated more accurately rather than following a fixed schedule [14].

2.2. Methods

Many cure monitoring methods exist, the majority of which are laboratory based and not suitable for industrial application. These methods require expensive equipment, typically only suited to working with small samples of restricted dimensions. Their destructive nature may also render the component useless following the cure monitoring procedure. Therefore, the following analytical equipment and methods are omitted as they cannot readily be applied for in-situ industrial cure monitoring of WTRB [15]:

Impractical Analytical instruments:

- Differential scanning calorimeter (DSC).
- Fourier transforms infrared spectrometer (FTIR).
- High performance liquid chromatography (HPLC).
- Gel permeation chromatography (GPC).
- Nuclear magnetic resonance [16].

Table 2
Cure monitoring methods applicable to WTRB production.

Section	Cure monitoring method
2.2.1	Dielectric
2.2.2	Acoustic
2.2.3	Ultrasonic
2.2.4	Thermal
2.2.5	Fibre optic strain gauge

Fig. 13. Typical dielectric cure monitor sensors [www.e-thermal.com].

Destructive analytical instruments:

- Rheometers.
- Dynamic mechanical analysers (DMA).
- Torsional braid analysers (TBA).
- Dynamic dielectric thermal analysers (DETA).

A number of methods have been identified [17] which offer the possibility of in situ monitoring of the WTRB cure process and shall be examined further (Table 2).

2.2.1. Dielectric cure monitoring

Dielectric analysis is a well-established method [15] and considered to be the most mature in-situ cure monitoring technology [18]. Dielectric cure provides a robust indirect measurement of cure by giving information on the viscosity of thermoset resin [18]. The use of dielectric measurements for cure monitoring is typically performed with sinusoidal excitations at specific frequencies. A current waveform is obtained by applying a step change voltage to the material. The frequency dependant dielectric properties can therefore be calculated from the Fourier transform of the current waveform [15]. In this approach a small sensor is placed in contact with the resin. A voltage is applied to the element by an electronic impedance analyser that is connected to the sensor and measures impedance. The sensor response is affected by the resin polar side groups, as the cure reaction advances the mobility of the polar groups decreases. Therefore the resin dielectric constant and the impedance of the resin sensor combination change. Thus, resin viscosity is related with the impedance of the sensor [18].

The main disadvantage of this method is the difficulty to relate the sensor measurement to the resin mechanical properties [18].

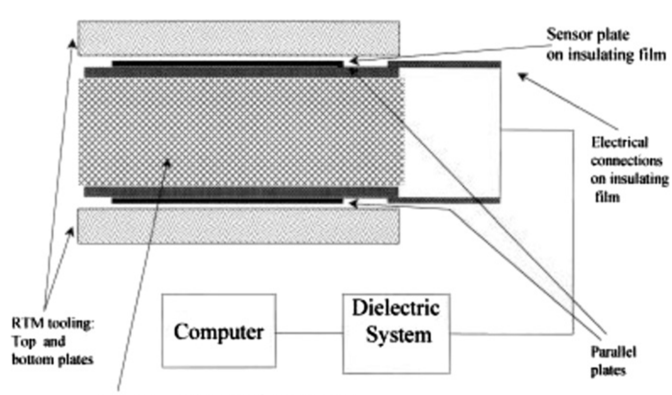

Fig. 14. The integration of a parallel plate dielectric sensor within an RTM tool [19].

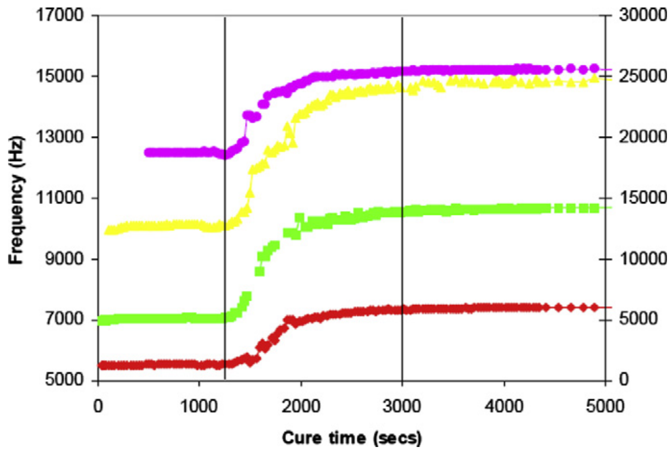

Fig. 15. Observed increase in amplitude of acoustic natural frequency responses of a curing polyester resin [17].

The typical response shows the change in resin viscosity indicating when cure is complete but does not give any indication of residual cure strain. Practical disadvantages of using typical dielectric sensors also include:

- Limited to localised cure measurement [19].
- Intrusive size of embedded sensors adversely affects the mechanical performance of the finished component (Fig. 13) [19].
- Critical contact surface, poor connection and impurities determine irreproducible data [18].
- Conductive materials such as carbon can effect results and require special treatment [20].
- Conductive reaction by-products such as water are known to cause inaccurate results [21].

Two dielectric cure monitoring configurations are generally utilised in industry. The use of individual dielectric embedded sensors is applicable to the low volume flexible tooling WTRB production. The sensors are embedded within the component and will remain there for the component life span. Specific disadvantages are that only cure local to the sensor is monitored and the sensor may act as a stress concentrator, adversely effecting component mechanical performance [19]. The alternative method is the use of plate sensors, measuring through the entire component thickness. The plate method requires a matched set of moulds with integral sensors that remain part of the tooting (Fig. 14). this method offers the advantage of measuring a larger area of cure along with reusable sensors [19]. However, the process is only typically suited to RTM with two rigid mould halves.

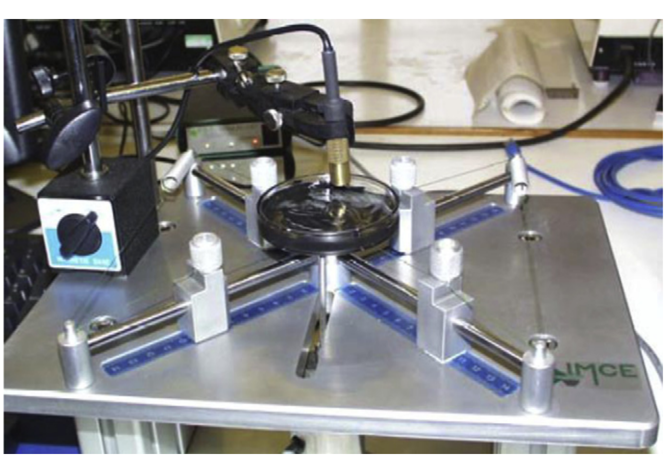

Fig. 16. Acoustic emissions monitoring of a test specimen mounted on taut wires to allow free vibration [17].

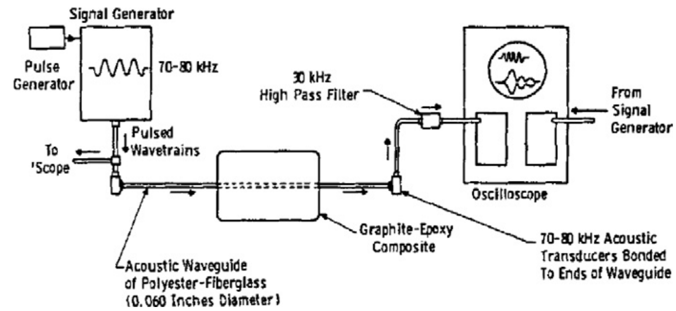

Fig. 17. Acoustic emissions monitoring using a waveguide [20].

2.2.2. Acoustic cure monitoring methods

Acoustic monitoring of resin cure has been investigated as early as 1955. In which pulsed 2.2–2.4 MHz wave trains were transmitted through curing polyester resin. Large changes in the longitudinal wave velocity and attenuation were recorded. These changes were believed to have been correlated with the degree of polymerisation and cross linking [20]. In practise a vibration is induced in the curing component by a mechanical impulse or sound wave excitation. The response vibration is detected using a transducer and the signal is analysed [17]. The response received is dependent upon component geometry, elastic properties and density of the curing material. Therefore changes in the response signal can be used as a measure of changes in material stiffness and density and therefore cure [17].

The natural frequencies of the material clearly increase in amplitude as the cure process advances due to increased stiffness (Fig. 15) [17]. Therefore, this method enables the opportunity to characterise stiffness and residual stresses. However, a correlation of acoustic data with material physical properties is required [15].

Difficulties exist with the method which may limit its feasibility in industrial applications. The mould configuration must allow free vibration of the specimen (Fig. 16) [17], the common problem of low signal to noise ratio is likely to occur in vibration damped mould situations [15]. The equipment could also be subject to external interference from vibration caused by vacuum pumps, mould expansion or contractions. The use of a waveguide is required for high temperature moulding which remains within the component and could be detrimental to structural integrity (Fig. 17).

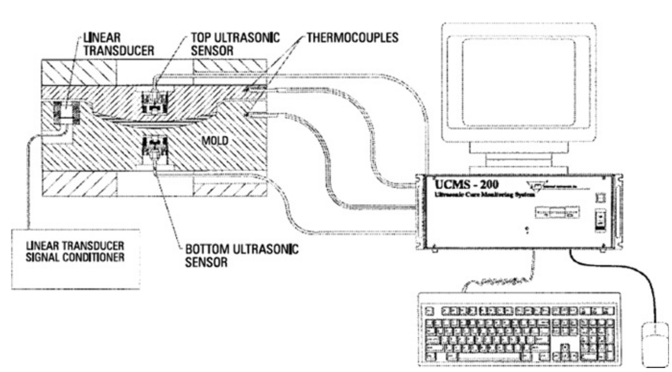

Fig. 18. Typical acoustic cure monitoring mould set up [21].

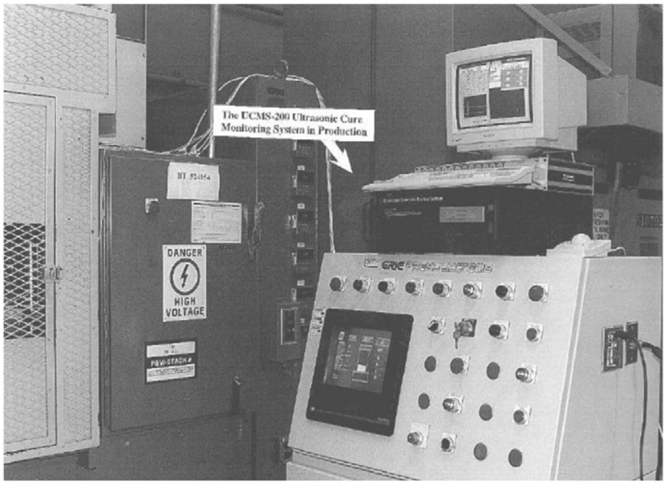

Fig. 19. Automated ultrasonic cure monitoring in an industrial application [21].

However, despite these difficulties, the application of acoustic emission analysis during the cure cycle of bonded joints within the aerospace industry shows future promise. AE monitoring has successfully recognised bond quality in a number of situations with aims to extend the technique into low cost reliable industrial monitoring procedures [22].

2.2.3. Ultrasonic cure monitoring methods

Ultrasonic cure monitoring consists of velocity measurements of ultrasonic waves. The speed of sound in a material is dependent on its density and modulus. Therefore, the time delay between transmission and received signal can reflect the state of the cure directly where thickness and density variations are negligible [17]. The ultrasonic velocity increases as cure progresses giving an immediate indication of increased in product density and mechanical stiffness [17].

Ultrasonic techniques demonstrate ability to detecting visco-elastic property changes. However, they suffer disadvantages associated with the use of acoustical impedance matching coupling medium between the piezoelectric transducer and the test material. The presence of a coupling medium can cause large transit time errors, change the waveform and hence effect the accuracy of the velocity measurement [18].

Two methods of ultrasonic measurement exist, through transmission measuring compression waves and pulse echo measuring

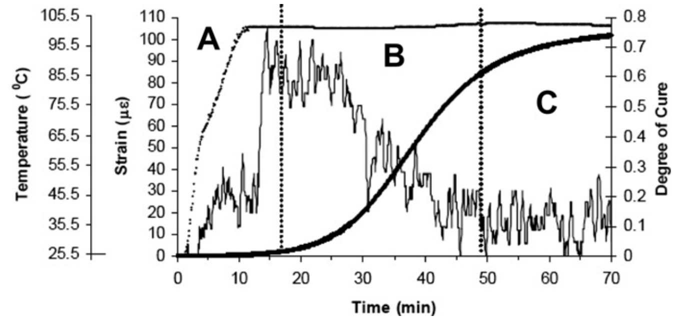

Fig. 21. Transverse strain measured using FBG sensors showing thermal expansion (A), polymerisation shrinkage (B) and complete cure reaction (C) [25].

shear waves. Shear waves are more sensitive to the end of cure, when most of the network structure has developed but more difficult to apply in practise, so compression waves are often used. The through transmission method requires two transducers but is preferred to echo method which relies on the reflected signal, therefore susceptible to signal loss [18].

Typically ultrasonic cure monitoring consists of non-intrusive transducers mounted in both halves of the mould, in the through transmission configuration (Fig. 18). This configuration of ultrasonic cure monitoring has been successfully deployed in an industrial compression moulding process (Fig. 19).

2.2.4. Thermal cure monitoring

Heat is generated during the curing chemical reaction known as exotherm. Both peak temperature and the time taken to reach peak can be used as guides to establish cure progression. The maximum temperature can be used to indicate maximum reaction rate of the material. For direct comparisons to be made, the location of the sensor, component size and geometry should remain constant [17].

It is often useful to monitor both the material and environment temperature in order to identify exotherms and other temperature dependant material behaviour which does not directly reflect variations in the ambient temperature [17]. Temperature sensors are readily employed in industrial applications with commonly used methods listed below [17]:

- Thermocouples
- Infrared/thermal imaging
- Resistance temperature detectors (RTDs)
- Thermo chromic paints/coatings/liquid crystal sheets (TLCs)

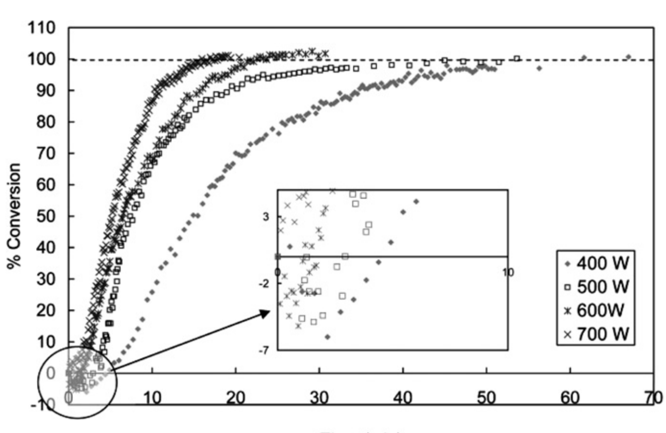

Fig. 20. Monitoring microwave cure conversion over time using a Fresnel reflector at alternate microwave power levels [23].

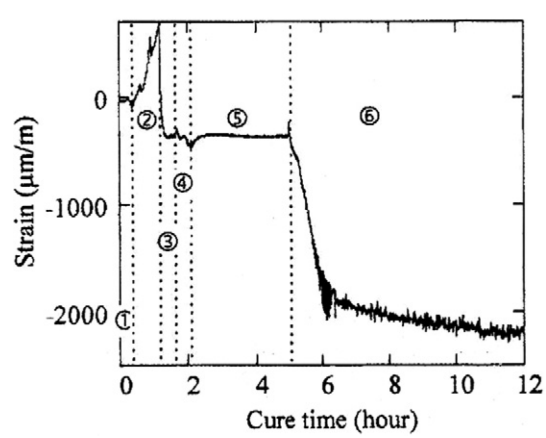

Fig. 22. Longitudinal cure strain monitored using FBG sensors showing thermal expansion (2), polymerisation shrinkage (3), post cure dwell (4–5) and thermal shrinkage during cooling (5) [24].

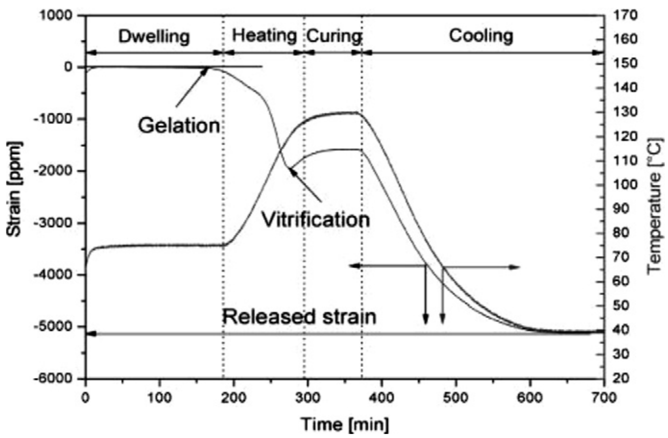

Fig. 23. Longitudinal cure strain monitored with FBG sensors identifying gelation and vitrification points [26].

2.2.5. *Fibre optic cure monitoring*

Two different methods of cure monitoring can be performed using fibre optics, Fresnel's reflection and strain monitoring using FBG sensors. Fresnel's reflection fibre optic cure monitoring operates on the principle of monitoring, change in the refractive index between a cleaved fibre end and the resin interface. A single mode fibre coupled to a laser diode and photo detector is used to monitor the cure. This sensor type is able to detect the increase in refractive index with isothermal cure and therefore follow the polymerisation. The results show clearly when cure is complete (Fig. 20) and compare well with other methods of cure monitoring [23]. However, the information obtained is qualitative and can only be conducted under isothermal conditions, where the effect of temperature on refractive index is minimised [23].

Recent advances in analytical instrumentation and fibre optic sensor systems have enabled the collection of in-situ cure kinetic data during the processing of reinforced plastics [14]. FBG sensors used in structural health monitoring (Section 1.3.2.2) can also be utilised during curing to accurately record strain resulting from cure shrinkage, thermal expansion and autoclave pressure in an industrial process [24]. Typically, the FBG sensor is embedded within the composite material with its protective coating removed by chloroform [18]. The wavelength shift and therefore strain is then monitored throughout the cure process. Typically the initial stage shows thermal expansion of the resin as the component is

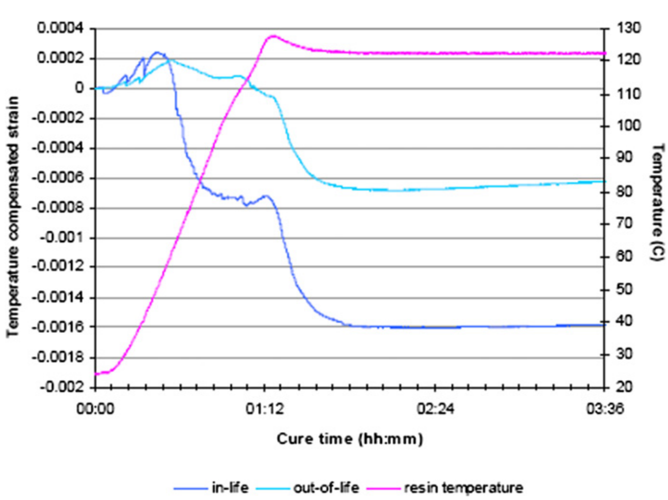

Fig. 24. Longitudinal cure strain of epoxy compared to expired shelf life epoxy monitored using FBG sensors [17].

Table 3
Overview of cure characteristics detectable with the main monitoring techniques [17].

Method	Cure capability/sensitivity					
	Resin fill	Minimum viscosity	Gel point	End of cure	Degree of cure	Other
Temperature	✗	✗	✗	✓	✓	Reaction rate
Acoustic	✓	✗	✓	✓	✓	
Ultrasonic	✓	✗	✓	✓	✓	Regression
Dielectric	✓	✓	✓	✓	✓	Post-cure
Fibre Bragg	✗	✗	✓	✓	✗	Post-cure Tg CTE Relaxations SHM

heated (Fig. 21). Thermal expansion is then followed by polymerisation shrinkage as the resin begins to cure. Once the component is allowed to cool a further increase in negative strain can be seen due to thermal shrinkage (Fig. 22). Experimental studies have also enabled the identification of gelation and vitrification points (Fig. 23).

Monitoring strain using FBG sensors can show when polymerisation is complete. The residual strains can be used to characterise component quality, as higher residual strains are considered detrimental. Manufacturers attempts to shorten cure schedules to reduce process costs have been shown to adversely influence properties in a study conducted using FBG cure monitoring [26]. It is also possible to detect raw material defects such as expired shelf life of resins (Fig. 24).

Monitoring cure strain using FBG sensors can give a quantitative result which identifies when cure is complete. As FBG sensors may already be embedded for the purpose of SHM, cure monitoring may come at little additional cost to WTRB manufacturers. However, the sensitivity of exposed FBG sensors to damage may require extra precautions during their integration in the manufacturing process. FBG cure strain monitoring also offers the opportunity of characterising material properties in relation to the cure conditions and allows previously unavailable feedback from the curing process.

3. Conclusion

All cure monitoring techniques considered were found to give an indication of when cure is complete (Table 3), allowing a manufacturer to terminate the heat supply promptly and capitalise on cycle time and energy savings. However, temperature, acoustic, ultrasonic and dielectric methods offer no indication of residual internal stresses effecting component quality and performance. Acoustic, dielectric and ultrasonic methods require additional equipment, processes and expertise resulting additional cost. If FBG sensors are to be present for SHM then their use in monitoring the cure process would incur minimal extra cost. FBG cure monitoring has the potential to accurately determine the completion of cure and the accumulation of residual internal stress. Such quantitative information can be used to characterise and improve the curing process.

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